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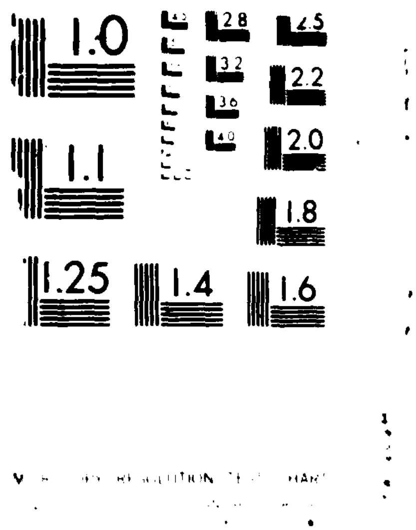
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A TRIDENT SCHOLAR PROJECT REPORT

NO. 142

A TRADE-OFF STUDY OF SONAR PERFORMANCE AND POWERING REQUIREMENTS FOR UNCONVENTIONAL SONAR DOMES

UNITED STATES NAVAL ACADEMY
ANNAPOLIS, MARYLAND

1987

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U.S.N.A. - Trident Scholar project report; no. 142 (1987)

A TRADE-OFF STUDY OF SONAR PERFORMANCE AND POWERING REQUIREMENTS FOR UNCONVENTIONAL SONAR DOMES

A TRIDENT SCHOLAR PROJECT REPORT

by

JENNIFER CULBERTSON

MIDSHIPMAN FIRST CLASS, '87

U. S. NAVAL ACADEMY

ANNAPOLIS, MARYLAND

Bruce Johnson

Dr. Bruce Johnson, NSE Department

Accepted for Trident Scholar Committee

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ABSTRACT

The results of an investigation of the resistance characteristics and powering requirements of unconventional sonar domes are presented and discussed. The sonar dome designs evaluated were below-baseline domes incorporating long prismatic sections designed to house large planar passive arrays. The cross-sectional area, and the longitudinal length of the domes were systematically varied. The predicted powering requirements for a parent destroyer hull form appended with different designs of sonar domes were compared to the relative improvements in sonar capabilities that each dome design could offer. These changes in powering requirements were translated to fuel costs to provide a basis for an economic trade-off analysis.

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A TRADE-OFF STUDY OF SONAR PERFORMANCE AND POWERING REQUIREMENTS FOR UNCONVENTIONAL SONAR DOMES

INTRODUCTION

Anti-submarine warfare (ASW) is a primary mission of destroyers and frigates. To be effective as an ASW platform, a vessel must first be able to detect enemy submarines. This requirement makes the design of sonar domes an important consideration in the overall design of combatants.

Presently, the majority of destroyers and frigates in the U.S. Navy are fitted with the SQS-53 sonar or its predecessor, the SQS-26 sonar. The SQS-26 sonar, which is housed in a bow dome and has both active and passive capabilites, was developed in the early 1960's for the Bronstein class of frigates (FF 1037). This sonar system and the below-baseline bow dome in which it is housed have served as the standards for all succeeding classes of ASW frigates and destroyers. Although the SQS-53 is a newer system, it is based on the SQS-26 with the improvements representing refinements in digital phasing. It is housed in the same type of dome as the SQS-26 sonar system (Polmar, 1984).

Size is an important factor governing sonar capabilites. In general, improving the performance of a given system requires increasing the surface area of the individual transducers and thus the size of the overall array. Larger arrays allow the use of lower frequencies. Because lower frequency signals suffer less attenuation in traveling through water than do higher frequency signals, they yield an increase in detection range. Both passive and active systems can gain this extention in range, but passive capabilities are the primary concern here. When a combatant uses her active sonar she compromises herself by possibly revealing her position to targets in the vicinity. When using a passive system, she does not take this chance; she merely eavesdrops on sound signals already traveling through the water. Enhancing an ASW platform's passive capabilites therefore takes priority for the current Soviet threat. Another advantage for a passive sonar with low frequency capabilities is that the high intensity noises from ship machinery and propellers are usually in the low frequency range (Frieden, 1985).

With the refinement of modern sonar technology, a system employing large passive planar arrays that has significantly better performance characteristics than the present SQS-53 sonar could feasibly be developed. Long arrays running up to one-third the length of a ship would provide the opportunity to increase transducer size and thus to lower the operational frequency sensitivity and to improve the overall performance. This level of technology in sonar design is available at present. What is not available is a suitable dome in which to house such a large sonar system. Because the U.S. Navy has used the same basic sonar for its ASW frigates and destroyers since the early 1960's, little recent research has been conducted in the area of sonar dome design, especially in the area of long, unconventional sonar domes (Cooke, 1969).

The design of long, unconventional domes presents many challenges to the naval architect. A large, below-baseline dome would affect many design considerations including the overall seakeeping and maneuvering capabilities of a vessel. The matter of longitudinal strength for the ship and for the long sonar dome would have to be addressed as well. Other factors influencing the design would be requirements for dry-docking and anchor handling. The most obvious factor that would need to be considered, however, would be the powering requirements. Because a long dome would have significantly more surface area than the present SQS-53 sonar dome, the frictional resistance would definitely be increased. If this increase in frictional resistance could be off-set by a decrease in another component of total resistance--specifically wave-making resistance--then the penalty in terms of increased powering requirements could be minimized.

Since the early 1900's, naval architects have often employed above-baseline bow bulbs to reduce the wave-making resistance of relatively slow, full-form ships such as tankers. A bow bulb causes waves that combine with the wave system produced by the the ship itself. If these two sets of waves combine destructively to negate each other, then the overall height of the wave system decreases and the wave-making resistance likewise decreases. To create this effect, particular attention must be paid to the design of the bow bulb. Today bow bulbs are even being incorporated into the design of some high-speed combatants, for example the Italian Maestrale class frigate. That bow bulbs can reduce wave-making resistance over certain speed ranges is well known (Hoyle, 1985). That the same holds true for sonar domes is less certain. Bow bulbs are above the baseline of a ship and are not designed to house any particular structure. Sonar domes, however, need to extend below the baseline to give transducers enough submergence to reduce the possibility of cavitation and bubble sweep down. Also, the design of sonar domes is restricted by the requirement that they house the appropriate sonar arrays.

Since significant improvements in passive sonar capabilities could be realized by putting long arrays in long, below-baseline domes, the design of such domes warrants study. In ship design, a gain or improvement in one area is generally coupled with compromises in other areas. This would be true for sonar design. Before serious improvements in the passive capabilities of dome-housed sonars could be implemented, the effects on other areas would need to be weighed. This paper presents an investigation of some of the trade-offs in terms of powering requirements that would have to be made to improve sonar performance.

OBJECTIVES

The objectives of this Trident Scholar research project were three-fold:

(1) An investigation into the effects on total resistance and wave-making resistance of changing the cross-sectional shape of a below-baseline sonar dome.

(2) A comparison of changes in powering requirements to improvements in sonar capabilities for dome designs of systematically varied length.

(3) An evaluation of the Fastship computer-aided hull form design software and the Ship Resistance Prediction Method (SRPM) flow code recently set-up at the U.S. Naval Academy Hydromechanics Laboratory.

METHOD OF INVESTIGATION

I. SUPPORTING SYSTEMS

A. OVERVIEW: All phases of this Trident Scholar research project were rooted in computer-aided hull form design and computer analysis. The three systems used to support this trade-off study were: (1) the Fastship computer-aided hull form design program which is resident on an Hewlett-Packard 320 computer in the U.S. Naval Academy's Hydromechanics Laboratory; (2) the Ship Resistance Prediction Method (SRPM) wave resistance flow code which is installed on the Gould 6050, a main frame system maintained by the Computer-Aided Design and Integrated Graphics (CADIG) department at the U.S. Naval Academy; and (3) a data reduction and fuel consumption analysis routine which was devised by the author using the SuperCalc 4 spreadsheet package from Computer Associates used in conjunction with a Zenith 181 personal computer. All hull form design work was done interactively on the computer rather than on the drafting board. Powering predictions were calculated by the flow code. No model tests were made for this investigation. Instead, the emphasis of this project was on the advantages of computer supported analysis in developing and testing series of hull forms at the preliminary investigative stage of design.

Figure (1) is a flow diagram illustrating the role that various computer systems played in this investigation.

B. FASTSHIP: The Fastship program is an inter-active system for both initial hull form design and modification. Design Systems and Services Inc. of Annapolis, Maryland developed this software package under contract with the U. S. Naval Academy as an improved version of its Fast Yacht system. A B-spline surface routine is used to create a file of points that defines a hull's surface. Once a Fastship surface file is created it can be transformed into a panel file which models the hull's surface as a combination of quadrilateral and triangular panels. Although a panel file does not provide the same degree of definition of the hull form as the surface file does, producing a panel file is necessary for coordinating the Fastship system with the SRPM flow code. Further information about the capabilities of Fastship are provided in the User's Manual (Design Systems and Services, Inc., 1986).

C. SRPM FLOW CODE: The hull form defined by a Fastship panel file can be transferred to the SRPM program to be approximated mathematically by a distribution of Havelock sources and sinks of varying strengths and analyzed by the SRPM flow code to evaluate the hull form's resistance over a

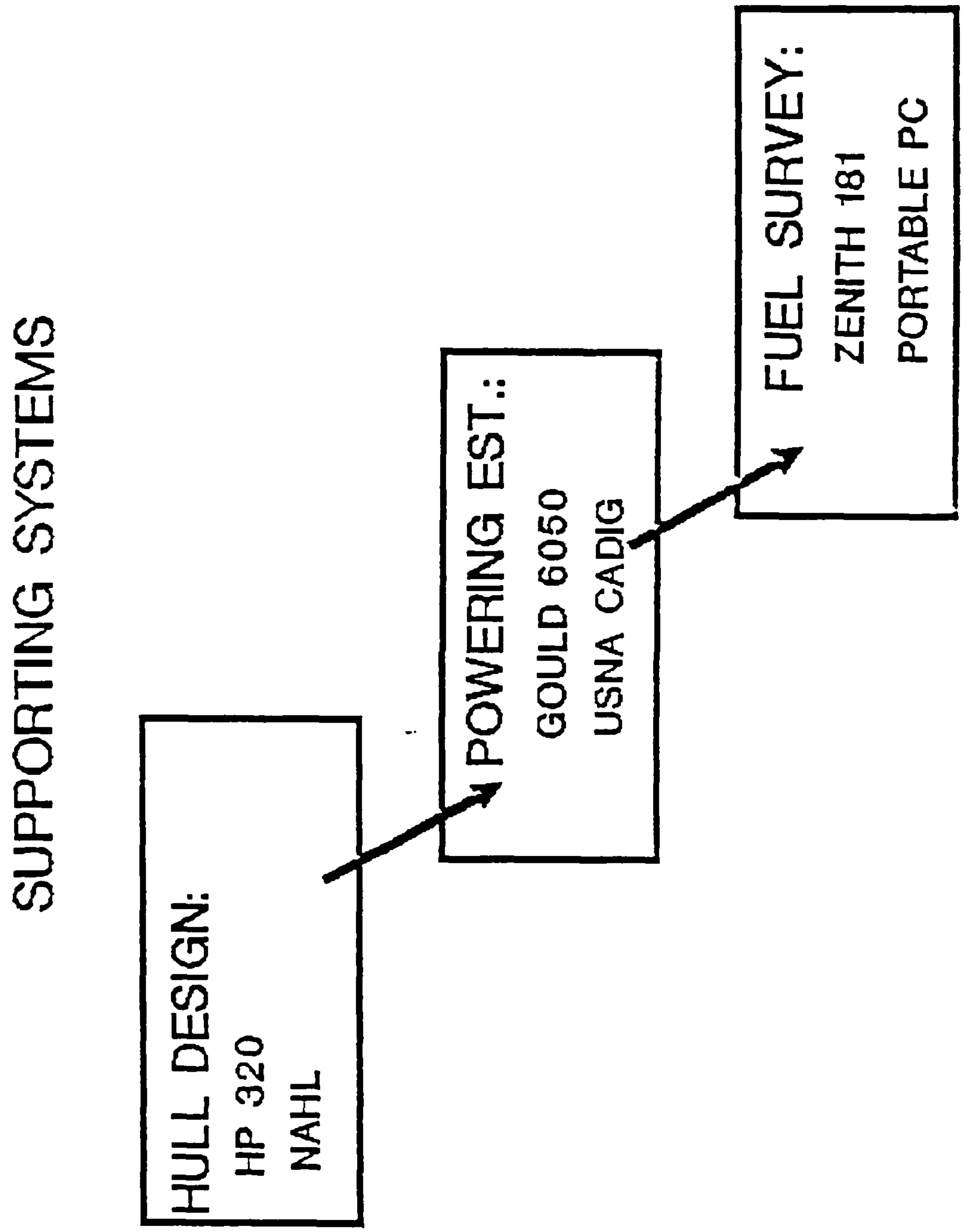

SUPPORTING SYSTEMS
HULL DESIGN:
HP 320
NAHL
POWERING EST.:
GOULD 6050
USNA CADIG
FUEL SURVEY:
ZENITH 181
PORTABLE PC

FIGURE (1)

given speed range. The SRPM flow code uses slender-ship theory to calculate wave-making resistance. From this, residual resistance is calculated empirically. Frictional resistance is calculated according to the ITTC '57 method (Harvald, 1983). Compensation for changes in trim with increasing speed can be made by the flow code if data on the trimming behaviour of the hull form is available. A detailed discussion of the supporting theory for the SRPM flow code and information on using this system is available in SRPM User's Manual (SAIC, 1986). As a preliminary verification of this flow code, the Naval Academy Hydromechanics Laboratory's staff has made comparisons of the powering predictions from SRPM to results from towing tank model tests for the Oliver Hazzard Perry class frigate (FFG 7) with and without bow bulbs. These tests are an extension to the Trident Scholar research project completed by Midshipman First Class Jeffery W. Hoyle in 1985. This verification study showed an agreement between the SRPM predictions and model tests that is at least equivalent to those for more sophisticated flow codes run on super-computers. The results of this study will be published in the near future.

D. DATA ANALYSIS: Calculations of yearly fuel requirements for various hull forms was based on information about the baseline hull form's typical operations and fuel requirements, and on powering requirements of the various hull forms relative to the baseline's. The SRPM flow code generated the necessary powering data in the form of effective horsepower at a given speed. Effective horsepower (EHP) is a measure of how much power is required in order to push or tow a ship through still water at a given speed. It is not a final measure of required engine horsepower since losses occur between the engine and the net power output of the propeller because of propulsion system inefficiencies. When considering different hull forms based on a parent form, however, EHP can be used as a comparison for powering requirements because the same type of shafting, propellers, and sea state can be assumed for each hull form.

EHP is a function of both velocity and total resistance. Total resistance, in turn, is a function of both velocity and wetted surface area. These terms are represented by the following equations:

$$RT = 0.50\ CT\ \rho\ V^2\ S \qquad (1)$$

$$EHP = (RT\ V)/(550\ \text{ft-lb/sec}\cdot\text{hp}) \qquad (2)$$

In the equations above, RT is total resistance in pounds. CT is the non-dimensional coefficient for total resistance and ρ is the value for density of water in slugs/ft . V is velocity in feet per second, and S is wetted surface area in square feet.

Although wetted surface area figures significantly in the determination of EHP, no attempt was made to keep either wetted surface area or displacement constant for different hull forms in this investigation. Instead, mean draft was the control factor; all evaluations were conducted for hulls floating at a draft of 20 feet corresponding to a displacement of 8100 long tons for the baseline DD-963. This choice of a controlling parameter was made because the emphasis of this investigation is on feasible designs for unconventional sonar domes. Meeting the appropriate criteria for housing sonar arrays is much more important than limiting wetted surface area for a dome to some arbitrary square footage.

Forming a ratio of EHP of one hull form to EHP of a baseline hull form provides a method for comparing the powering requirements of various designs. Using a baseline hull form standardizes the comparisons. The significance of an EHP ratio is that it provides a measure of the percentage change in the amount of power that must be provided to one hull form to have it make the same speed as the baseline hull form. For example, an EHP ratio of 1.00 would reflect that both the new design and the baseline hull form would require the same amount of horsepower to make the same speed. A ratio of 1.20 would indicate that the new design would need twenty percent more horsepower than the baseline hull form to make the same speed.

EHP ratios utilizing the Spruance destroyer fit with the SQS-53 dome as a baseline as well as ratios referenced to a Spruance hull without any dome are used throughout this investigation. To gauge the relative improvements or penalties in powering requrements for Spruance hulls with various sonar dome designs, the ratios referenced to the SQS-53 design are used for the fuel comparison analysis. The fuel analysis was based on data contained in a recent Naval Engineers Journal (Schlappi, 1982). In conjunction with this information, the EHP ratios were used to develop a spreadsheet routine to calculate changes in fuel requirements for each new hull form. The calculations and assumptions made in developing the routine used for this analysis are explained in the "Results and Discussion" section of this paper.

II. TRADE-OFF STUDY:

A. OVERVIEW: The investigation for this trade-off study was divided into the four major sections of a baseline study, a shape study, a length series, and a fuel consumption analysis. Figure (2) is a diagram showing the relationship of these sections.

B. BASELINE STUDY: The first section of the investigation was a baseline study. A basic destroyer or frigate type hull form with the SQS-53 sonar dome was needed as a standard for comparison throughout the investigation.

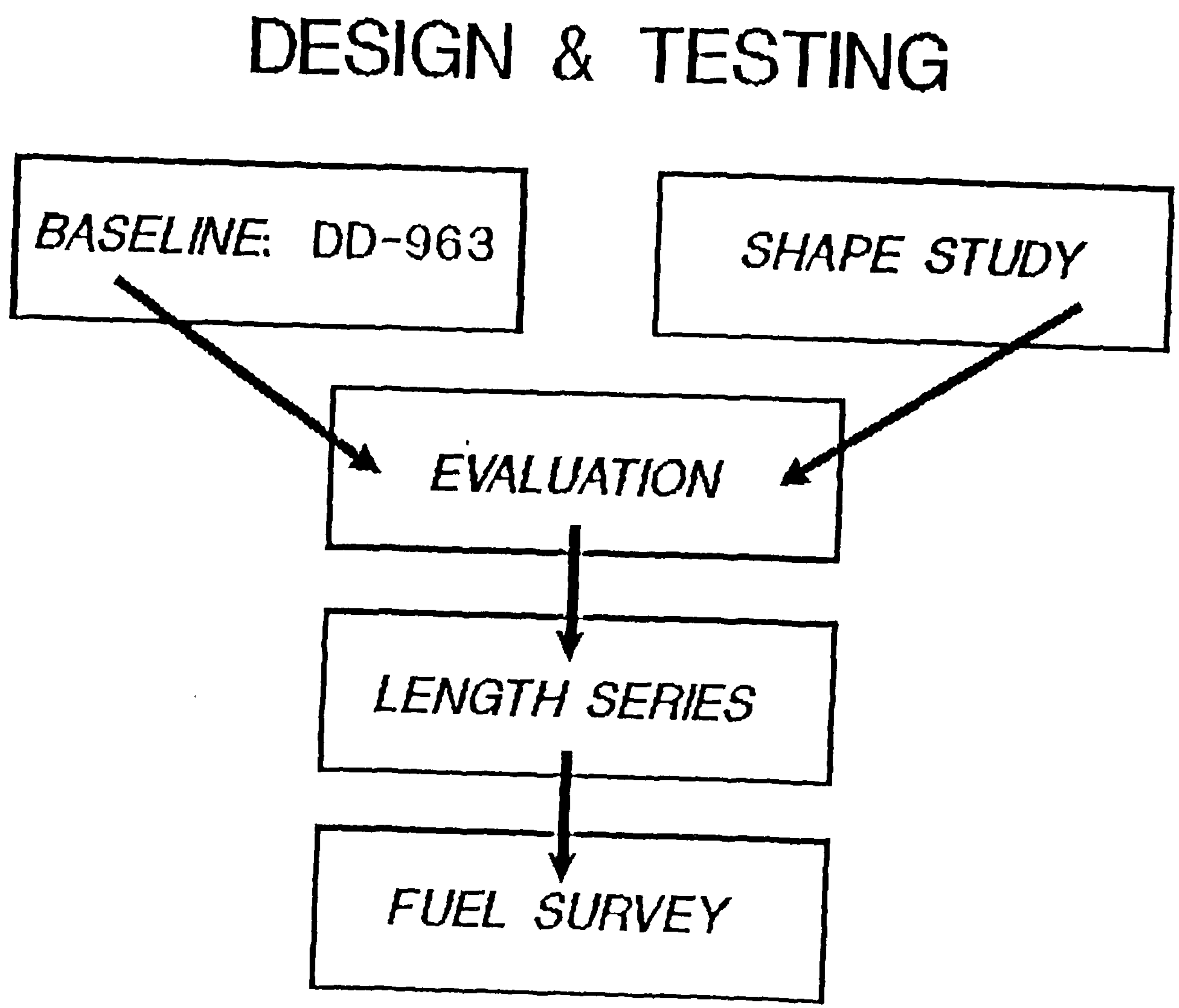

DESIGN & TESTING
BASELINE: DD-963
SHAPE STUDY
EVALUATION
LENGTH SERIES
FUEL SURVEY

FIGURE (2)

The Spruance class destroyer (DD-963) was selected because it: (1) is designed with a SQS-53 sonar dome; (2) is the parent hull form for three classes of U.S. Navy vessels; and (3) has unclassified lines.

Once the DD-963 was chosen as the baseline hull form, its resistance was estimated analytically. This step of the investigation involved creating a hull form on the Fastship system to match the existing lines of the Spruance class destroyer as identically as practical, and then running the SRPM wave resistance flow code on this hull form to evaluate the resistance and powering characteristics. The SRPM flow code was run on this hull form initially employing an option of the program that accounts for the trim that occurs as the speed of the ship increases and once without accounting for trim. The EHP curves from these two SRPM evaluations were compared. Because the SRPM trim option uses a data file compiled from model tests of typical destroyers to predict trim rather than calculating it for each hull form, all hull forms in the investigation were tested without using the trim option. This was done to standardize the results as much as possible.

To conclude the baseline study, the DD-963 baseline hull form was modified on the Fastship system by removing the SQS-53 sonar bow dome. The SRPM flow code was run on this domeless hull form to provide a second standard of comparison for the investigation.

C. SHAPE STUDY: The shape study involved designing four different cross-sectional shapes for sonar domes. Each shape was designed so that a prismatic dome developed from the shape could as a minimum house an array composed of transducers 8 ft deep and 2 ft wide running longitudinally for any arbitrary length of dome. These cross-sectional shapes were then developed into below-baseline domes of an arbitrarily chosen 150 ft. length overall and fit to the baseline domeless hull form using the "Fastship" program. For each appended hull design particular attention was paid to the fairing back into the hull aft of the dome in order to effect a smooth longitudinal distribution of cross-sectional area. The SRPM flow code was then run on each appended hull form. The wave-making resistance, and the EHP predictions for each appended hull form were compared to corresponding data for both the baseline hull with the SQS-53 dome and the domeless hull.

From each basic cross-section shape a series of three appended hull forms was created. The three dome designs varied in cross-sectional area. The influence of changing transverse area was investigated because of the conclusions of Midshipman Hoyle's 1985 Trident Scholar research project investigating the design of above-baseline bow bulbs for high-speed ships. This project found that the larger the transverse area of the bulb, up to the limit investigated, the greater the magnitude of change in total resistance

(Hoyle, 1985). The first design in each series had a dome meeting the minimum geometric requirements to house two transducers and necessary structure. The second hull form in each series had a dome of the same shape as the parent form but with a cross-sectional area 1.25 times that of the parent dome. The third hull form had a dome with 1.5 times the cross-sectional area of the parent dome. Estimated powering requirements for each series of hull forms was analyzed by SRPM flow code. The resistance and powering predictions from the SRPM analysis were compared between members of the same series to investigate trends in powering requirements caused by increasing transverse area for a given shape of dome.

D. LENGTH SERIES: From the shape study, the best family of cross-sectional shapes was chosen considering powering requirements, and feasibility of construction. The three cross-section designs from this family were then used to develop three series of domes with systematically varied length. All appended hull forms were created using the Fastship system. The domes were designed so that the prismatic--or constant cross-sectional shape--sections ran lengths of 10 ft, 20 ft, 40 ft, 80 ft, and 160 ft. These lengths were chosen based on relative sonar performance data provided by Naval Underwater Systems Center in Groton Connecticut for arrays of these lengths. It is in the long prismatic section of a dome that large planar arrays could most effectively be housed. For a given series, keeping the cross-sectional shape constant and doubling the length for each successive dome had the effect of doubling the surface area of the arrays that each dome could house provided that the depths of the arrays were held constant. All hull forms in the series were evaluated with the SRPM flow code for resistance characteristics and powering estimates.

E. FUEL CONSUMPTION ANALYSIS: Using the resistance and powering data for the length series, a survey of the changes in fueling requirements caused by varying the length of the sonar dome was completed. This survey was based on an operational profile for a typical destroyer detailing the percentages of time a destroyer is likely to be operating at various ranges of speeds (Schlappi, 1982). The results from the fuel survey for each length series were then compared to the gains in overall sonar capabilities made possible by lengthening the sonar dome. This analysis summarized the amount of additional fuel that would have to be carried on or provided to a ship like the DD-963 in order to gain different levels of improvement in sonar capabilities through the use of long planar arrays without compromising the ship's ability to perform its normal operations.

F. TRADE-OFF ANALYSIS: Using the results from the fuel consumption analysis, the change in fueling requirements was expressed in terms of costs to operate destroyers with the various sonar domes designed for the length series. These cost results were then compared to the gains in sonar directivity index that could be realized for each change in length of array for each dome design to produce a presentation of the penalties that must be paid for various levels of improvement of sonar capabilities.

RESULTS AND DISCUSSION

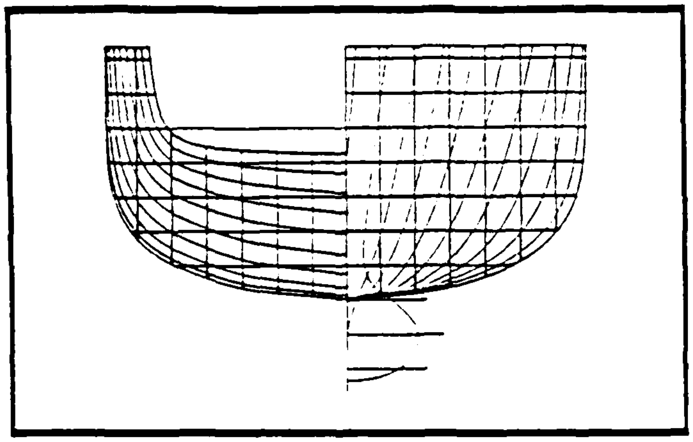
I. BASELINE STUDY

A. DESCRIPTION: For the baseline study, the resistance characteristics and the powering requirements were evaluated both for the Spruance destroyer with the SQS-53 dome and for the domeless Spruance hull form. Figure (3) shows the body plan for both of these baseline hull forms. The values for displacement and wetted surface area for each hull form are listed in Appendix A, Table (A1). Also, the percentage change in these values for the domeless design compared to the SQS-53 design are listed in Appendix A, Table (A1).

B. RESULTS: Figure (4) shows EHP plotted against ship velocity in knots both for the Spruance with the SQS-53 dome (BLo) and for the domeless design (BLx). Figure (5) is a plot of the ratio of EHP for the Spruance with SQS-53 dome compared to EHP for the domeless Spruance hull.

C. DISCUSSION OF RESULTS: As common sense would dictate both curves in figure (4) show that EHP increases as speed increases; it takes more power to go faster. The two curves differ from point to point, however, because the two hull

SQS-53
BASELINE
BLo



NO DOME
BASELINE
BLx

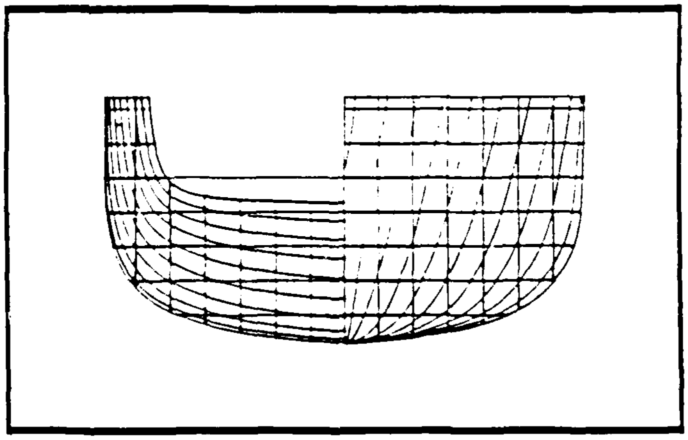


FIGURE (3)

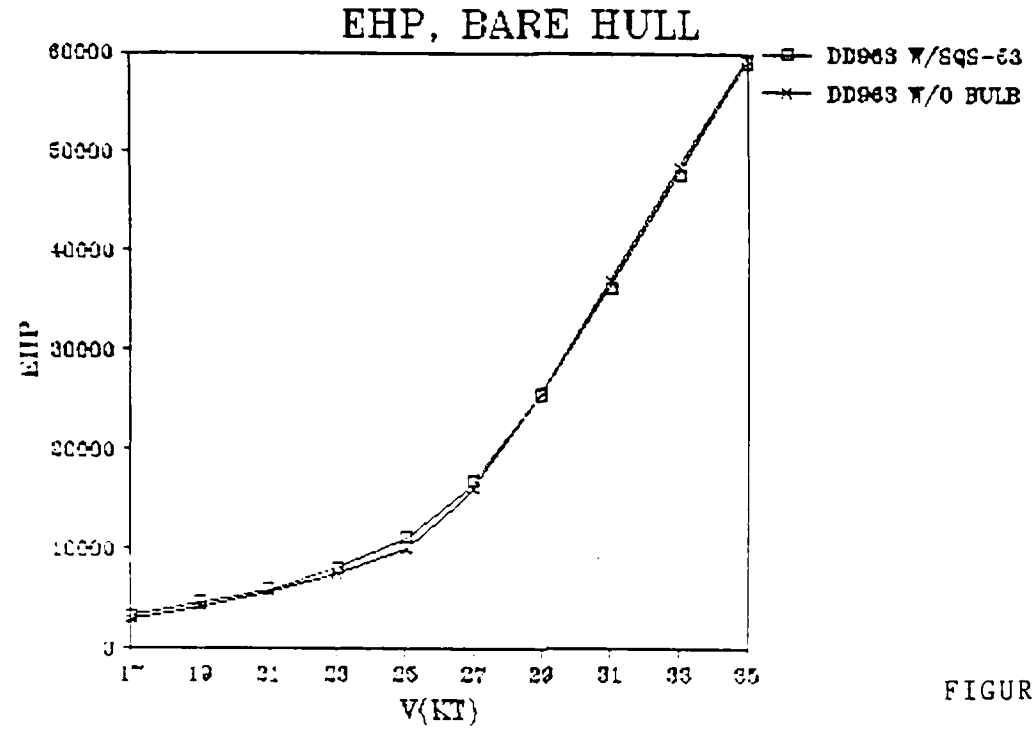


FIGURE (4)

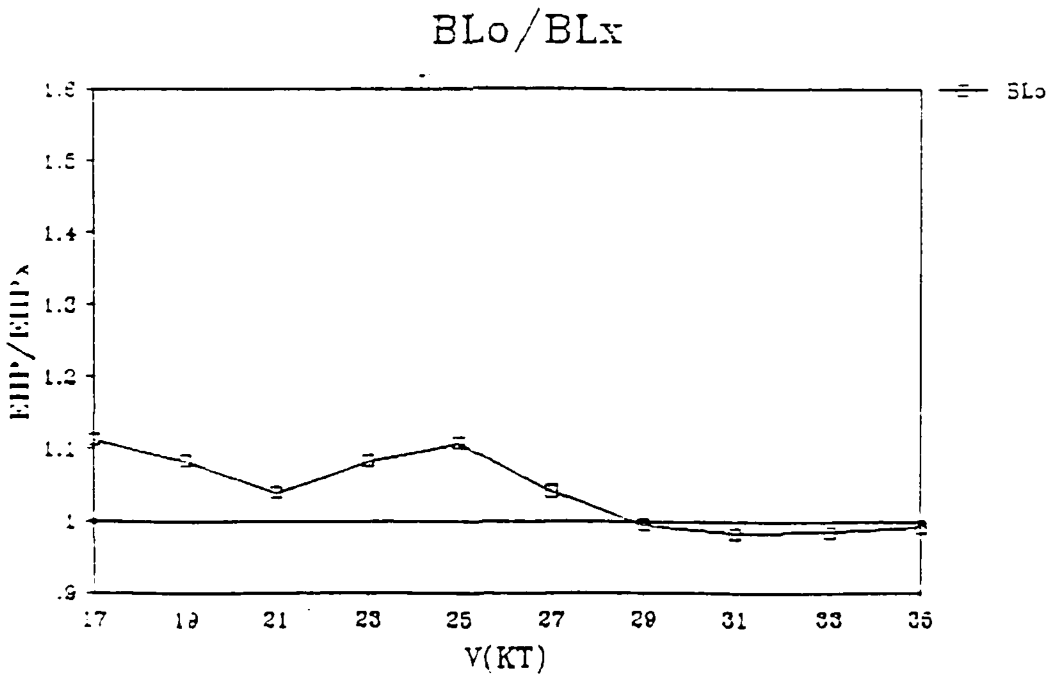


FIGURE (5)

forms have different resistance characteristics. Total resistance is made up of two major components; frictional resistance and residual resistance. Residual resistance, which is composed of wave-making resistance and eddy-making resistance, is influenced primarily by wave-making resistance. The contribution of eddy-making resistance to the total is small in comparison. Any number of factors can effect these different resistance components to influence the total amount of resistance. A factor that differs between the SQS-53 dome design and the domeless design is wetted surface area. For a relatively slender hull form, the frictional resistance contribution to total resistance increases steadily with increasing velocity according to the following equations:

$$RF = 0.5 \quad CF \rho V^2 S \tag{3}$$

$$CF = 0.075 / [(LOG10 \; Rn - 2)] \tag{4}$$

$$Rn = V \; L / \nu \tag{5}$$

where RF is frictional resistance, CF is the coefficient for frictional resistance, ρ is density of water, V is ship velocity and S is wetted surface area. Rn is the non-dimensional Reynold's Number and nu is the kinematic viscosity of water.

Wave making resistance makes a large contribution to total resistance at high speeds. Wave-making resistance is governed by the following equation:

$$RW = 0.5\ CW \rho\ V^2 S \qquad (6)$$

where CW is the coefficient for wave-making resistance. CW does not follow an empirical formula; for this investigation it was evaluated by the SRPM flow code. As the speed of a ship through water changes, the wave systems that each submerged portion of the ship generates and the way these wave systems combine also changes. A destructive combination of the wave systems decreases CW and likewise a constructive combination increase CW. This has the effect of making the relationship of CW to ship speed a hull form dependent variable in calculating total resistance and EHP.

Figure (5) shows that the presence of the SQS-53 dome has a slight favorable effect on the total resistance at speeds above 29 knots.

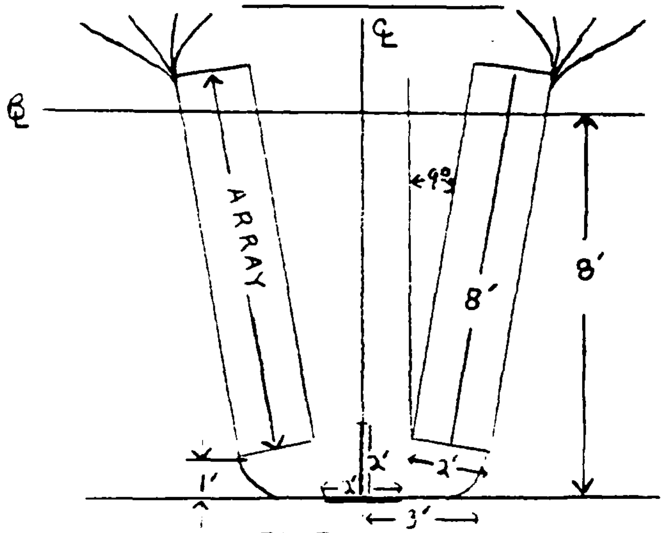
II. SHAPE STUDY

A. DEVELOPMENT OF SERIES: For a sonar dome design to be practical it must incorporate enough volume to house both the necessary arrays of sonar transducers and the structure needed for longitudinal strength and local strength. Beyond these basic requirements, efficient positioning of the arrays, as well as ease of construction of the dome must be considered. Criteria for dry-docking conditions, for example, lead to other limiting conditions such as draft constraints. Mr. Kurt Hansen of the Naval Underwater Systems Center in Groton, Connecticut provided information about the restrictions that would govern the possible geometric shapes for sonar domes housing long planar arrays. These guidelines were followed in designing the domes for the shape study.

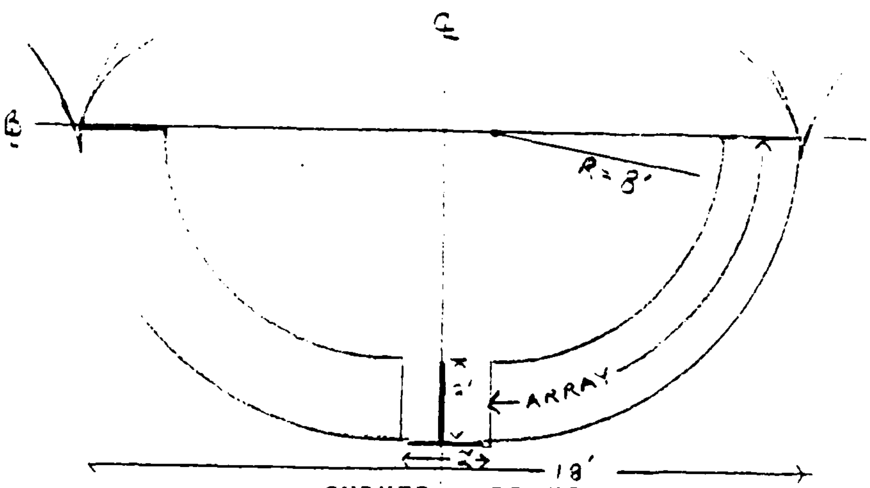
For this part of the investigation, all cross-sectional shapes were designed to house two passive planar arrays each measuring 8 feet in depth, 2 feet in width, and 120 feet in length. This length measurement was arbitrarily chosen since it did not affect the cross-sectional shape. The designs allowed space for a center vertical keelson measuring 2 feet at the flange and 2 feet at the web. Another restraint on the cross-section designs was that the maximum draft below the baseline could be no more than 8 feet due to standard keel block sizes used in dry-docking. Standard keel blocks are available in heights up to 12 feet and as low as four feet allowing an eight foot maximum distance below the keel for sonar domes. The depth below the keel of the SQS-53 sonar dome is 9.60 feet. Floating dry-docks which service destroyers and frigates with these sonar domes have wells cut into the dry-dock floor that can accommodate the domes. In light of the size of domes that could house sonar arrays up to 160 feet in length, the idea of using a well to house one of these long, unconventional domes is not practical.

Although advances in sonar technology make it possible to allow some curvature in the design of arrays, complex curvature--or curvature in more than one plane--greatly complicates the electronic design of the array. For this reason, and to facilitate construction, all domes were designed to have a long section of constant cross-sectional shape that could house the passive arrays. For sonar designs employing arrays without curvature, the optimum position in terms of sonar performance is at an angle of nine degrees off the vertical. For a curved array, any curvature back over the top of the array is undesirable; it is unnecessary to have an array positioned to listen upward above the baseline. The arrangement of arrays in a sonar dome should as a maximum cover 180 degrees of arc about the longitudinal axis. Figure (6) is a sketch showing the restrictions placed on sonar dome design both for designs

PASSIVE ARRAYS



FLAT ARRAYS



CURVED ARRAYS

FIGURE (6)

employing flat arrays and for designs incorporating arrays with curvature about the longitudinal axis.

B. DESCRIPTION OF SERIES: The guidelines discussed in the previous section were applied to the designs of the cross-sectional shapes evaluated in the shape study. Figures (A1) through (A5) in Appendix A provide body plan line drawings of the baseline Spruance class hull form appended with domes developed from the various cross-sectional shapes considered. Each figure shows a different family of designs. Each family consists of three dome designs with the same basic shape but varying in total dome cross-sectional area.

The displacement and wetted surface area for each hull form at a standard draft of 20 feet are listed in Appendix A, Table (A1). The values of percentage change also listed offer a comparison of the differences in displacement and wetted surface area for each hull form compared to the corresponding values for the Spruance class destroyer. The following is a brief discussion of the dome design for each family of domes evaluated for the shape study:

FAMILY A: The basic shape for these domes was a trapezoid with basically sharp corners at the lower edges and softer turns at the upper edges of the domes. The sides of these domes are angled at 9 degrees off the vertical centerline to optimize sonar performance. The planar sides and bottoms would facilitate construction for these designs.

FAMILY B: The shape for this series of domes is also a trapezoid. This family of domes varies from Family A only in the detail that the upper edges for these domes are sharp corners rather than rounded turns. This shape would be very easy to construct. It provides more flat area for the arrays below the baseline than does Family A.

FAMILY C: The basic shape for this set of dome designs was based on a modified semi-circular cross-section. These domes were designed to carry two curved arrays of 8 foot radius and 90 degrees of arc each. They are attatched to either side of a rectangle 8 feet in depth and varying in width. For the first dome design in the family which is designed to the minimum space requirements necessary to house two arrays, the rectangular section is 2 feet wide providing a flat section for the keelson. The next two designs in the family which represent a 1.25 increase and a 1.50 increase in dome cross-sectional area over the minimum requirements, have rectangular sections of 5.64 feet and 9.28 feet in width, respectively.

FAMILY D: The basic shape for this family of domes was developed from a half section of an ellipse with the major axis oriented transversely. It is similar in concept to the SQS-53 dome's shape. The SQS-53 sonar, however, houses cylindrical arrays that curve about a vertical axis rather about a longitudinal axis like this design. The design with minimum required space represents an ellipse with a major axis of 20 feet and a minor axis of 16 feet. Since the lower half of the ellipse forms the dome cross-section, this minor axis of 16 feet translates into a depth for the dome of 8 feet. Due to dry-docking constraints, this depth and therefore length of minor axis was held constant at 8 feet. The length of the major axis was adjusted to 25 feet and 30 feet to increase the total dome cross-sectional area by 1.25 and 1.5 times the minimum required area. These domes would carry passive arrays with the degrees of curvature complying to the shapes of the elliptical sides of the domes.

FAMILY E: The basic shape for these domes was also developed from an ellipse. The major axis, however, was oriented vertically for this family. This design is similar to the shape often used for above-baseline bow bulbs. To increase the area of the dome design, the major axis was lengthened which in turn increased the relative draft of the dome to exceed an 8 foot limit. The dome design with 1.25 the minimum cross-sectional area has a relative draft of 10 feet below the baseline. The design with 1.5 the minimum area has a draft of 12 feet below the baseline. Although these dome designs depart from the guidelines for maximum draft due to dry-docking, they were evaluated as part of the shape study to investigate the effect on resistance of changing the depth of a dome.

C. RESULTS: The resistance characteristics and powering requirements for Spruance hulls appended with sonar domes of the various cross-sectional designs discussed above were calculated numerically by the SRPM flow code. Figures (7) through (11) are plots of EHP ratio and ship velocity for the five families of hull forms evaluated in the shape study. EHP/EHPo refers to the baseline of the Spruance fit with the SQS-53 sonar dome. Figures (12) through (16) are also EHP ratio versus ship velocity plots for the five families of designs. Here EHP/EHPx ratios are referenced to the domeless hull form.

D. DISCUSSION OF RESULTS: From both the EHP/EHPo plots and the EHP/EHPx plots, the same trends are apparent for each family of dome designs. There is an increase in total powering requirements at speeds below 26 knots and a smaller reduction in powering requirements at speeds above 26 knots. When comparing the results within a given family of designs, all plots show that as transverse area increases for a given shape, the absolute value of the change in powering requirements increases. The domes with the greatest transverse area for a family, had the greatest increase in EHP at speeds below 26 knots, and also the greatest reduction in EHP at speeds above 26 knots. This result is similar to the guideline for above-baseline bulbs that the greater the transverse area of a bulb the greater the resulting effect on resistance. An equivalent guideline seems to hold true for below-baseline domes as well. Because all domes were designed to the same arbitrary length, the fact that the EHP ratio plots follow the same general shape suggests that the length of the dome rather than shape or transverse area will be the factor that

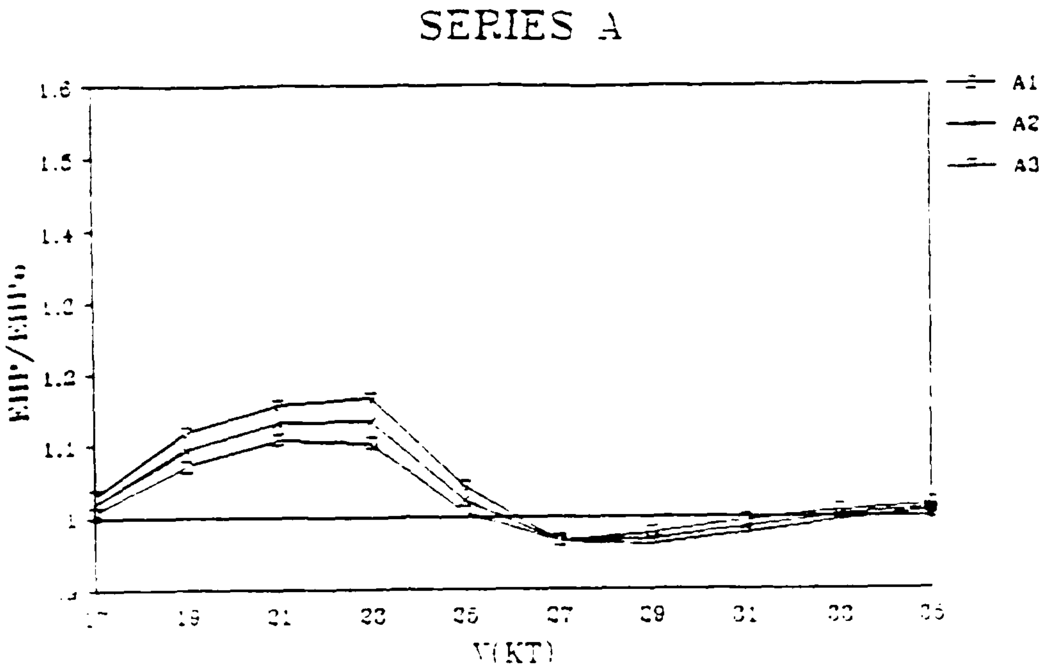


FIGURE (7)

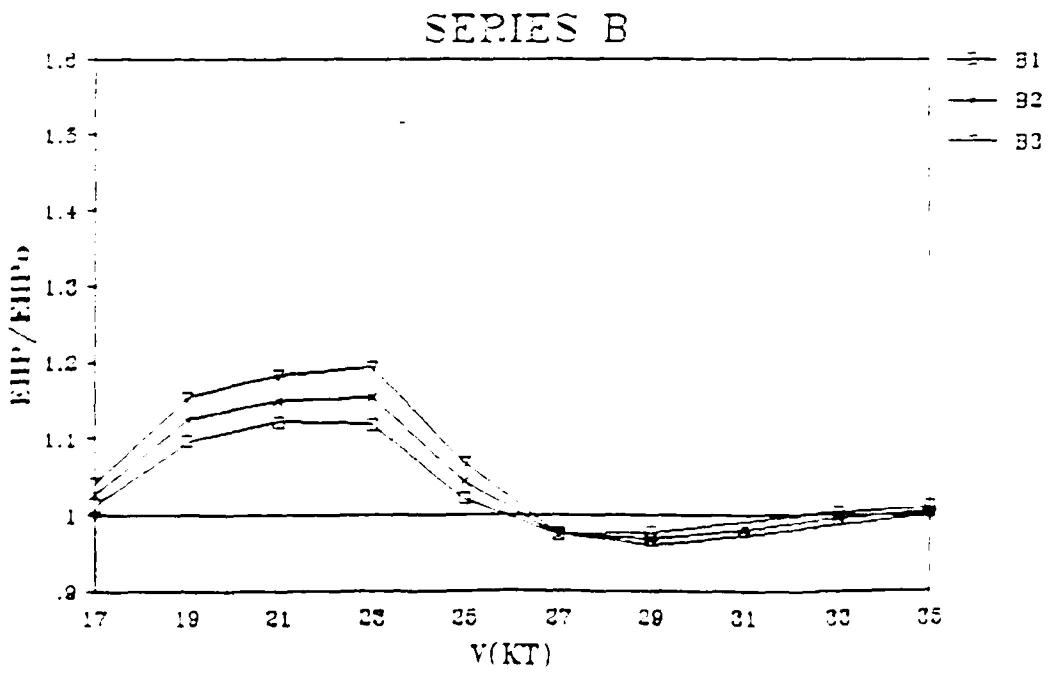


FIGURE (8)

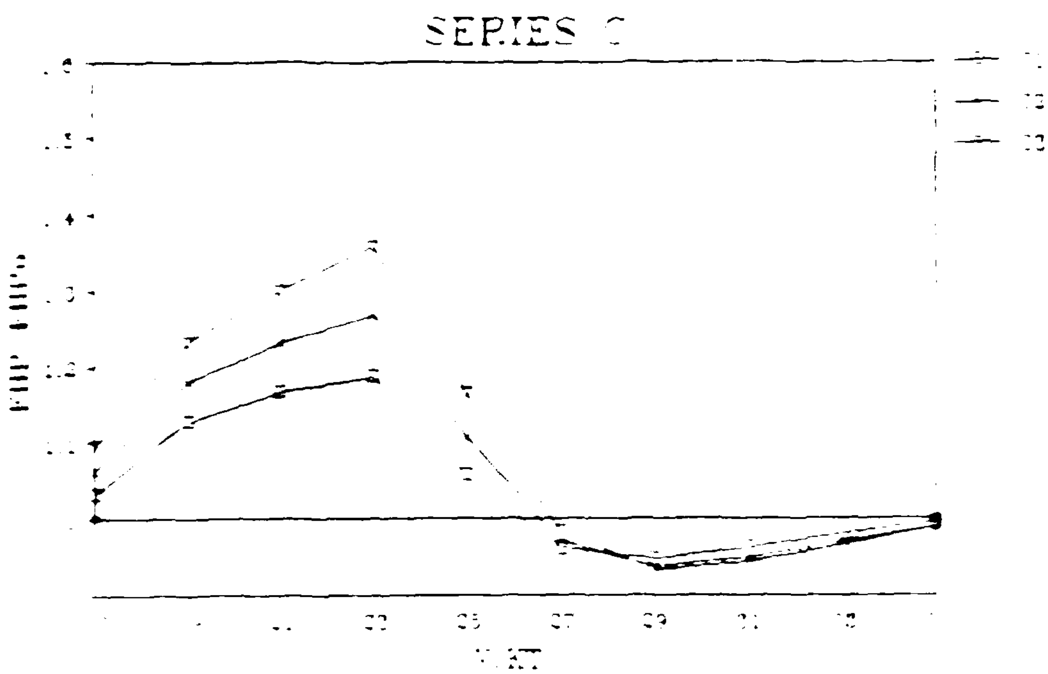


FIGURE 4

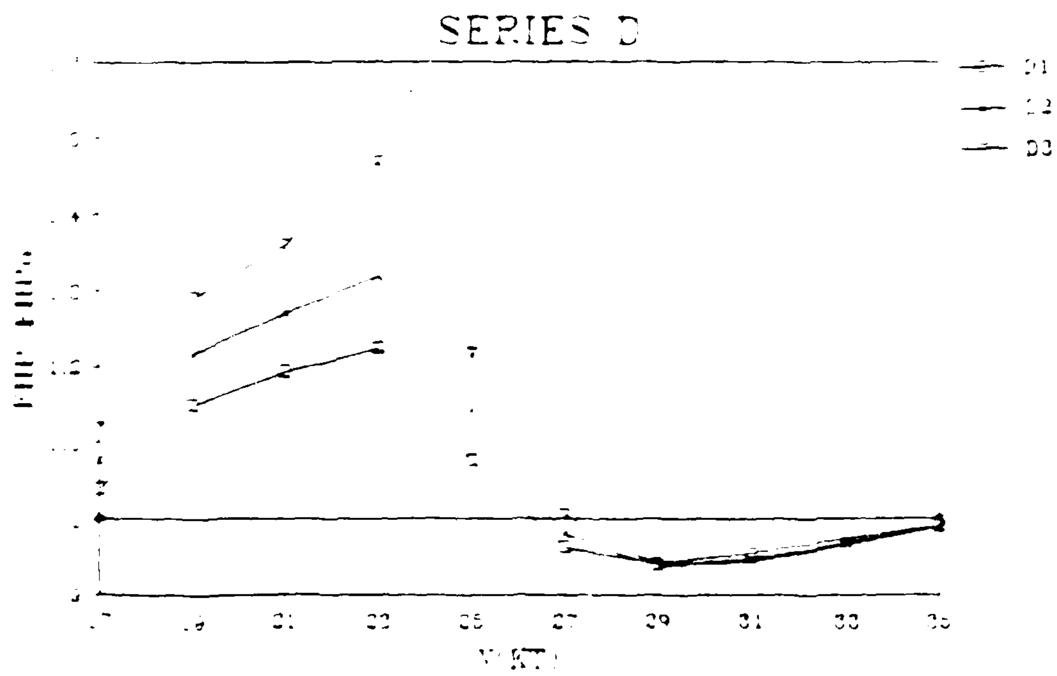


FIGURE (10)

SERIES E

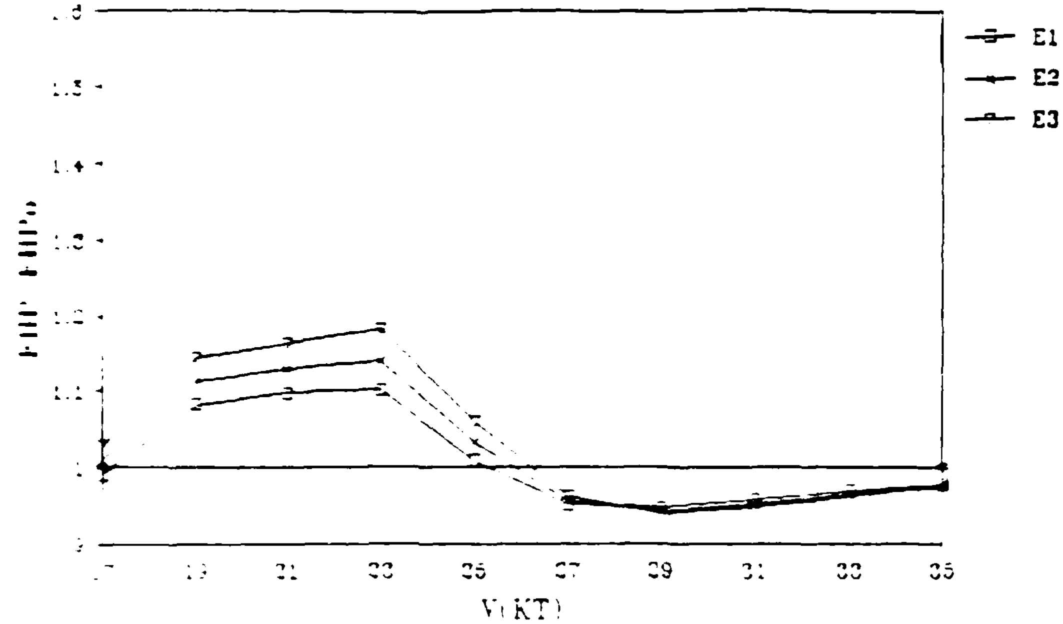


FIGURE (11)

SERIES A

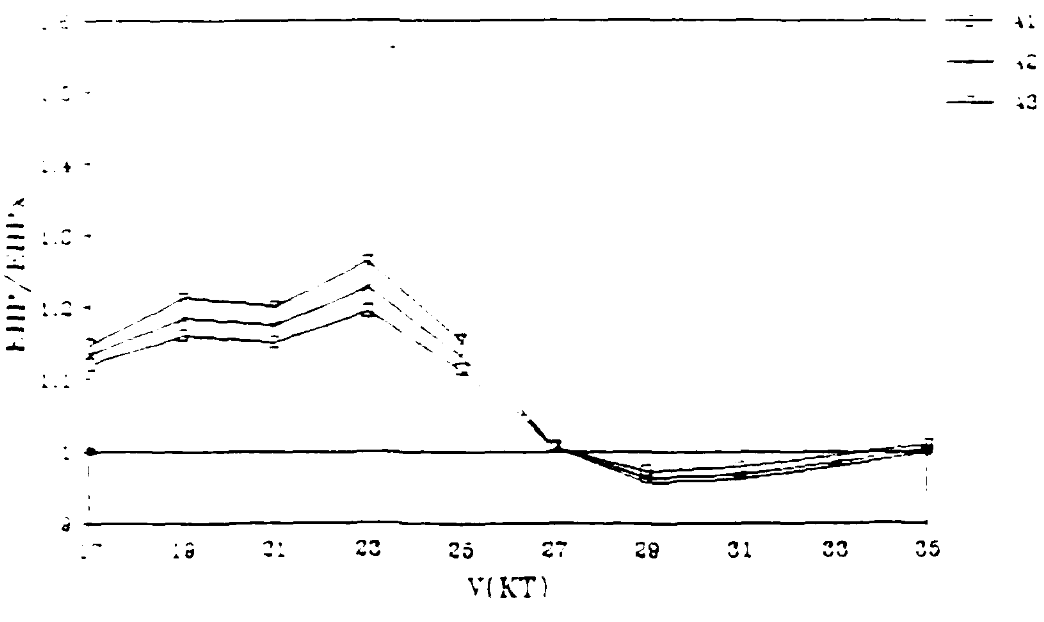


FIGURE (12)

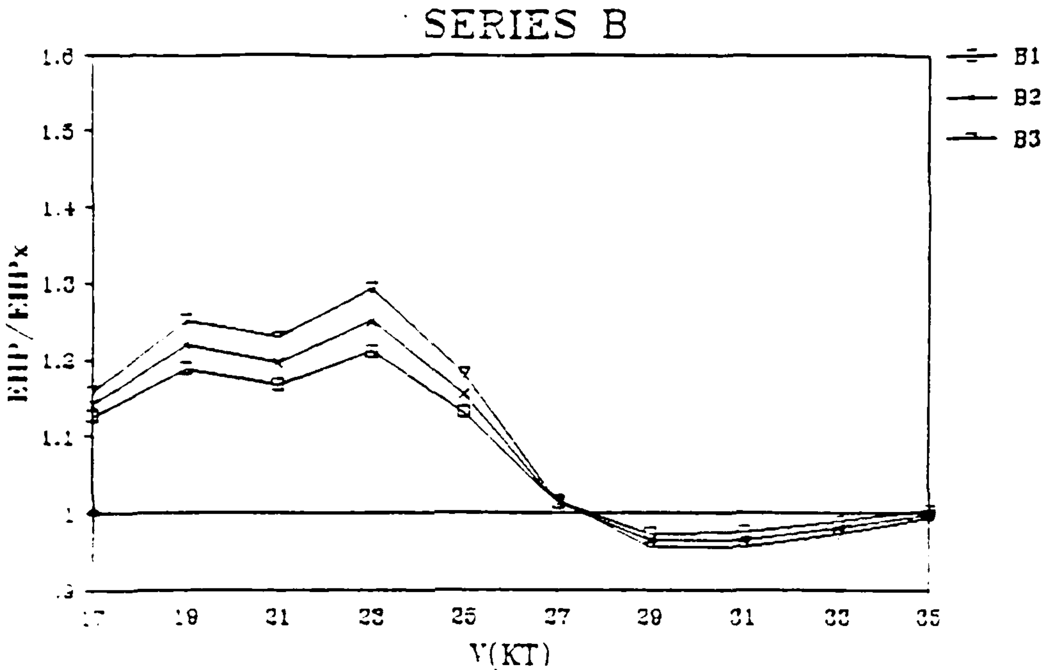


FIGURE (13)

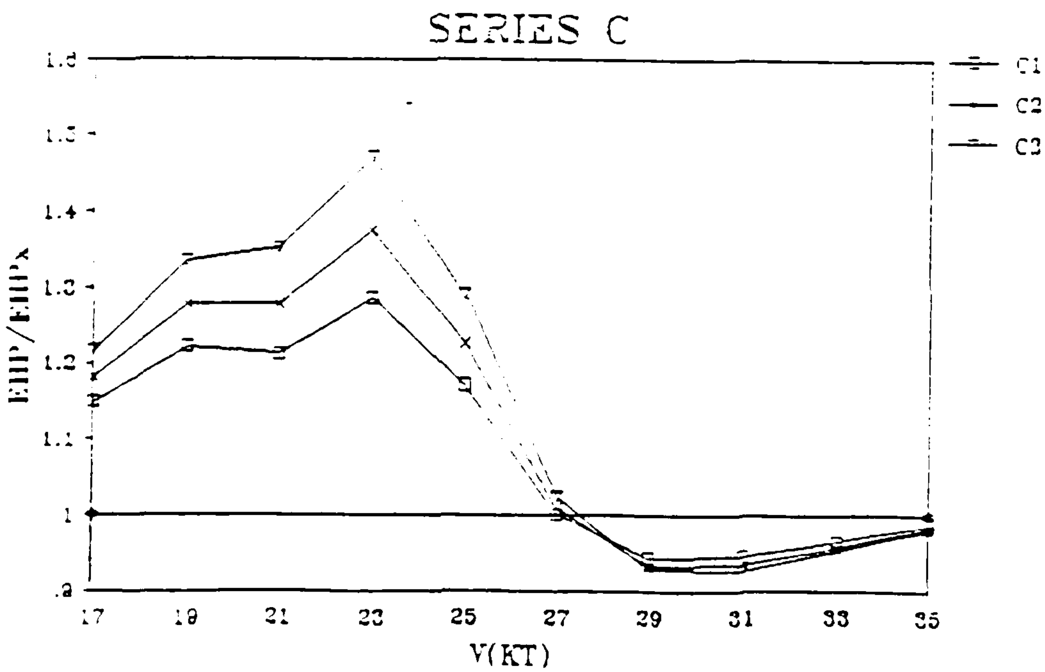


FIGURE (14)

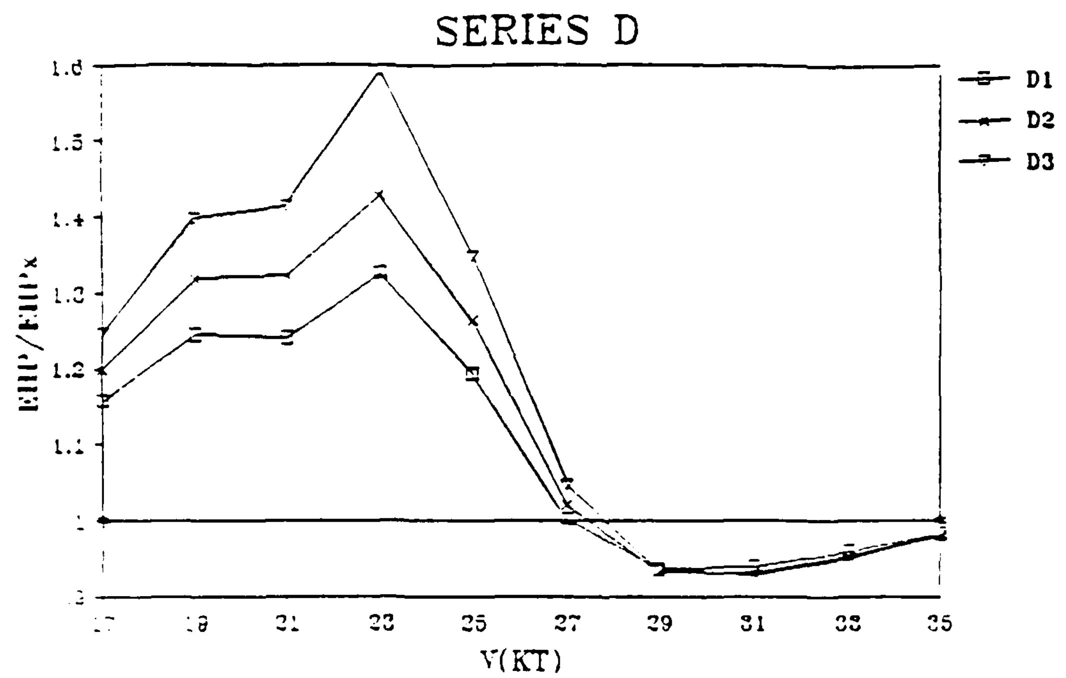


FIGURE (15)

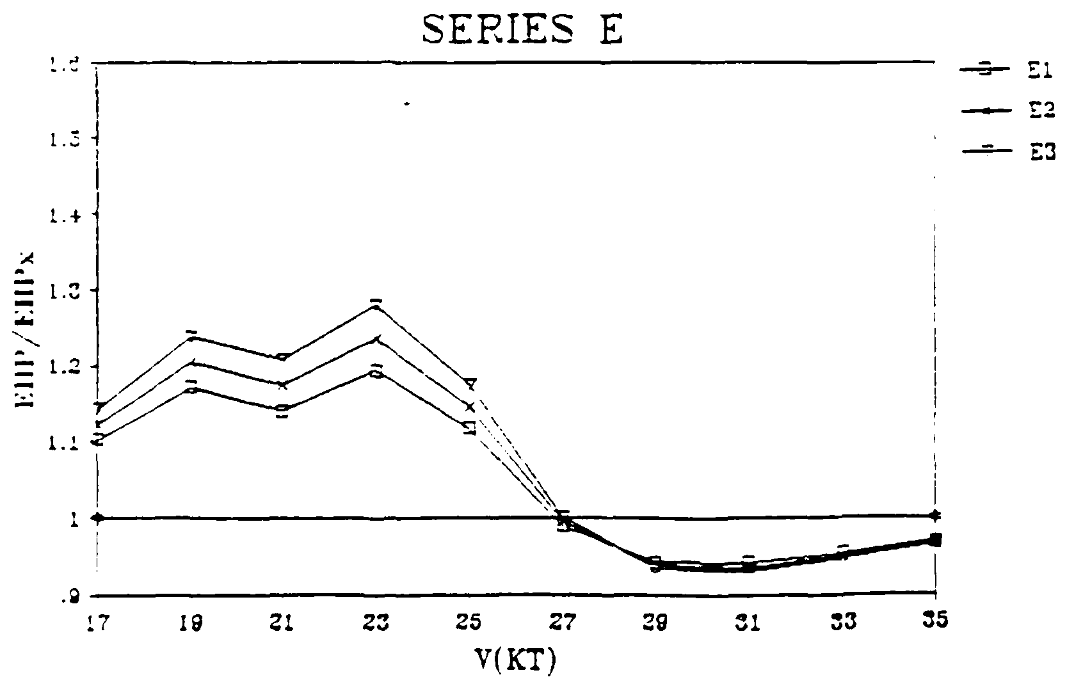


FIGURE (16)

influences at which speeds wave-making resistance is increased or decreased.

The largest reductions in powering requirements are recorded for the hull forms in families C and D. The maximum decrease in EHP for design C3 referenced to the SQS-53 design is 7%. For design D3 the maximum reduction is 6%. Unfortunately both families of designs showed increases in EHP in excess of 35%. These excessive increases in powering requirements would prohibit either shape C or D from feasibly being used to develop a sonar dome design.

Hull forms in family E display a favorable balance of increases and reductions in powering requirements. The maximum increase in EHP for design E3 is 18% referenced to the EHP for the Spruance fit with the existing SQS-53 dome. The maximum reduction in EHP is on the order of 6% for this family of designs. This family was not chosen to be the basis of the length series because the original cross-section design does not meet the requirement that total draft below the baseline be limited to 8 feet.

Hull forms in families A and B show very little difference between families in their EHP ratios. The maximum increase in powering requirements is less than 20% and the maximum reduction in powering requirements is on the order of 4% for both families. Because the 20% increase in

EHP is not prohibitively excessive, and the cross-section designs for families A and B have sonar dome depths limited to the required 8 foot maximum, the choice of shapes for the length series was narrowed to shape A and shape B. Shape B was finally chosen because it was designed to have more volume than shape A in order to more easily house sonar arrays. One caveat is introduced by the fact that shape B has sharp turns in its cross-sectional design. These corners would probably increase eddy-making resistance and thus total resistance of domes based on shape B in comparison to those developed from shape A. The almost identical EHP ratio results for families A and B, however, highlight that the SRPM wave resistance flow code is insensitive to changes in eddy-making resistance. Model tests would have to be conducted to determine the eddy-making resistance penalty of family B domes.

III. LENGTH SERIES

A. DEVELOPMENT OF SERIES: The third section of the investigation involved using the B family cross-section designs from the shape study to develop three series of domes of systematically varied length. The B1 dome shape served as the model for the first series; five domes with this cross-sectional shape were designed so that they could house arrays of 10, 20, 40, 80 and 160 feet in length. The B2 dome shape was the basis for the second series, and the B3 dome shape founded the third series. A margin of 32 feet of length was incorporated forward of the prismatic section in every dome design. This area forward of the region where planar passive sonar arrays would be housed was designed with the consideration that cylindrical active transducers would possibly be housed in the nose of the dome. The total transverse area of the prismatic region of each dome design, therefore, relates to the size of active arrays that could be used in the forward section. The wider the cross-section, the larger the nose. Beyond this consideration, all noses were faired to a shape that was as smooth and hemispherical as possible. The nose shape was not a parameter that was systematically varied in this investigation.

B. DESCRIPTION OF SERIES: Figure (A2) in Appendix A from the shape study section shows the body plans for the B1, B2, and B3 length series. Table (A2) in Appendix A summarizes the geometric characteristics of each dome design as well as the percentage changes in displacement and wetted surface area for each design compared to the Spruance hull fit with the SQS-53 dome.

C. RESULTS: Figures (17) through (19) are the EHP ratio plots developed from the powering requirements predicted by the SRPM flow code for the B1, B2, and B3 length series. EHP/EHPx refers to the ratio of the power required for a hull form in the length series compared to the power required for the domeless baseline.

D. DISCUSSION OF RESULTS: The EHP ratio plots for domes of a given length have the same general shape. For example, the dome in the B1 series that could house a 160 foot long array has the same shape EHP/EHPx plot as the domes in the B2 series and the B3 series that could also house arrays 160 feet in length. This observation supports the results from the shape study. Changing transverse area of a dome design increases or decreases the powering requirements at a given speed, but it does not greatly affect the relative trend of where these increases and decreases in powering requirements occur over a range of speeds.

For the three different length series, all the plots for domes designed to house 10 foot, 20 foot, 40 foot and 80 foot arrays follow the same general shape as the EHP ratio plot of the SQS-53 baseline compared to the domeless hull form shown in Figure (3). The trends in EHP ratios for domes able to house 20 foot arrays and those able to house

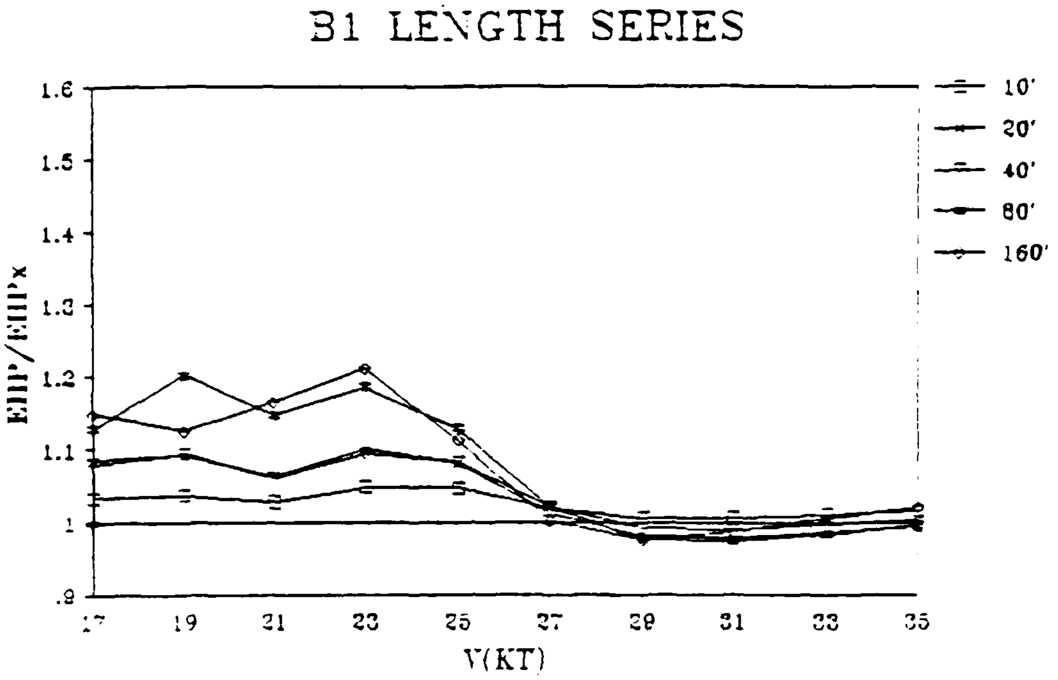


FIGURE (17)

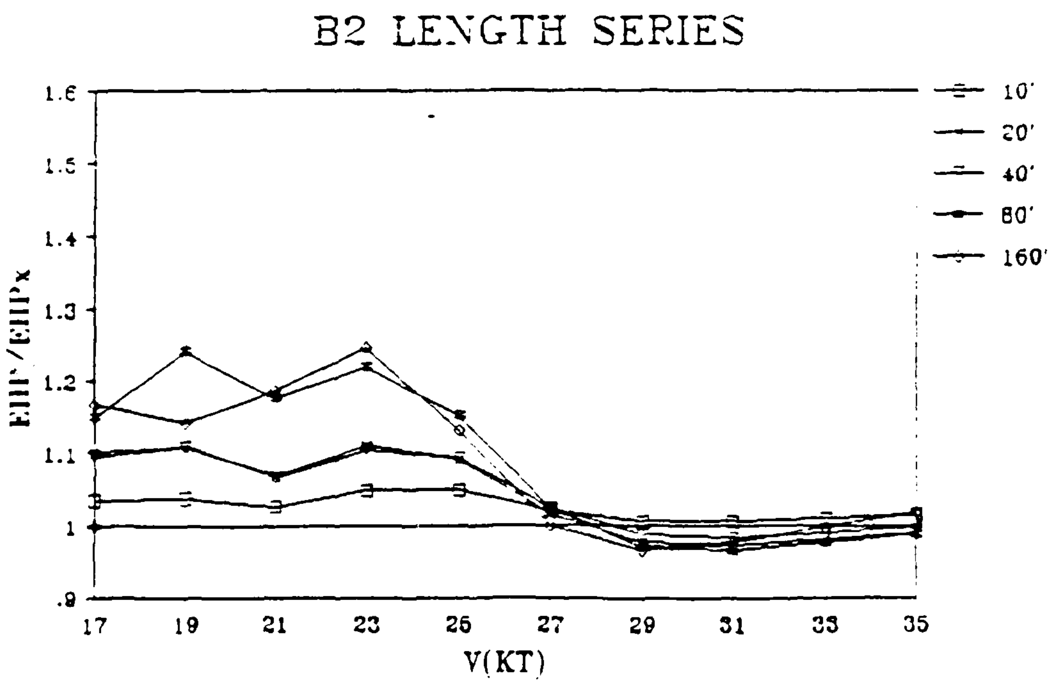


FIGURE (18)

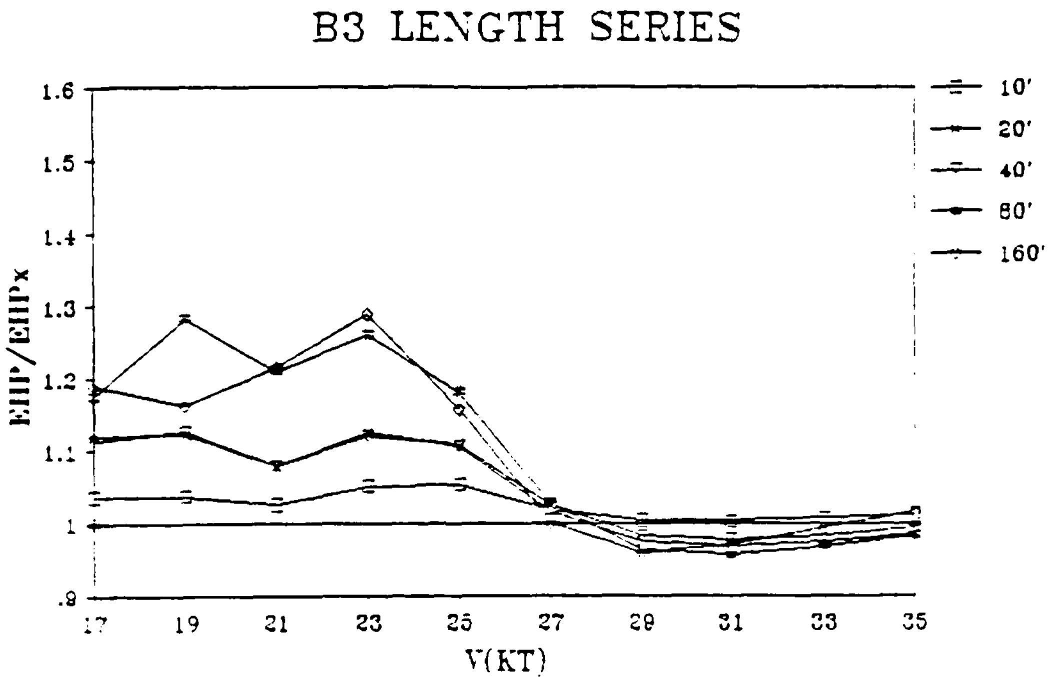

B3 LENGTH SERIES
1.6
1.5
1.4
1.3
1.2
1.1
1
.9
EHP/EHPx
17
19
21
23
25
27
29
31
33
35
V(KT)
10'
20'
40'
80'
160'

FIGURE (19)

40 foot arrays are almost identical. A noticeable departure from this trend in general shape is evident in the EHP ratios for the domes designed to house the 160 foot long arrays. For the other dome designs, the EHP ratio curves have local peaks at a ship speed of 19 knots. The opposite is true for the longest domes; local minimums occur at the 19 knot speed.

The departure of the EHP ratios for the longest domes from the general shape of the other plots suggests that the resulting combination of the wave system from the dome and the wave systems from the hull itself is definitely different from the resulting combination of wave systems for hulls with the other length domes. This result is similar to one of the conclusions made by Midshipman Hoyle about above-baseline bow bulbs. He suggested that the length and longitudinal location of bulb affect the phase of the wave system produced by the bulb and therefore alter the speeds at which wave-making resistance is reduced (Hoyle, 1985). The almost identical EHP ratio trends for the domes housing 20 foot arrays and those housing 40 foot arrays may mean that the wave system produced by both these domes is very similar.

IV. FUEL CONSUMPTION ANALYSIS

A. OPERATION PROFILE: In order to estimate the amount of fuel that a ship will consume in a given time period, it is first necessary to know how the ship will operate over the given time period. Figure (20) provides this information for the Spruance class destroyer. This operation profile, which shows the percentage of time underway that a Spruance class destroyer is likely to be operating at various speeds, was derived from unclassified information in a recent Naval Engineers Journal (Schlappi, 1982).

B. DEVELOPMENT OF ANALYSIS ROUTINE: The amount of fuel that a ship burns at a specific speed is directly proportional to the amount of horsepower required by the propulsion system to move the ship at that speed. The fuel required for a given speed in terms of long tons of fuel per hour can be estimated by the following equation:

$$(\text{long tons/hr}) = (EHP/PC) * (SFC/2240) \qquad (7)$$

where EHP is the total effective horsepower for a fully appended ship, PC is the propulsive coefficient included to account for ineffeciencies in the propulsion system, and SFC

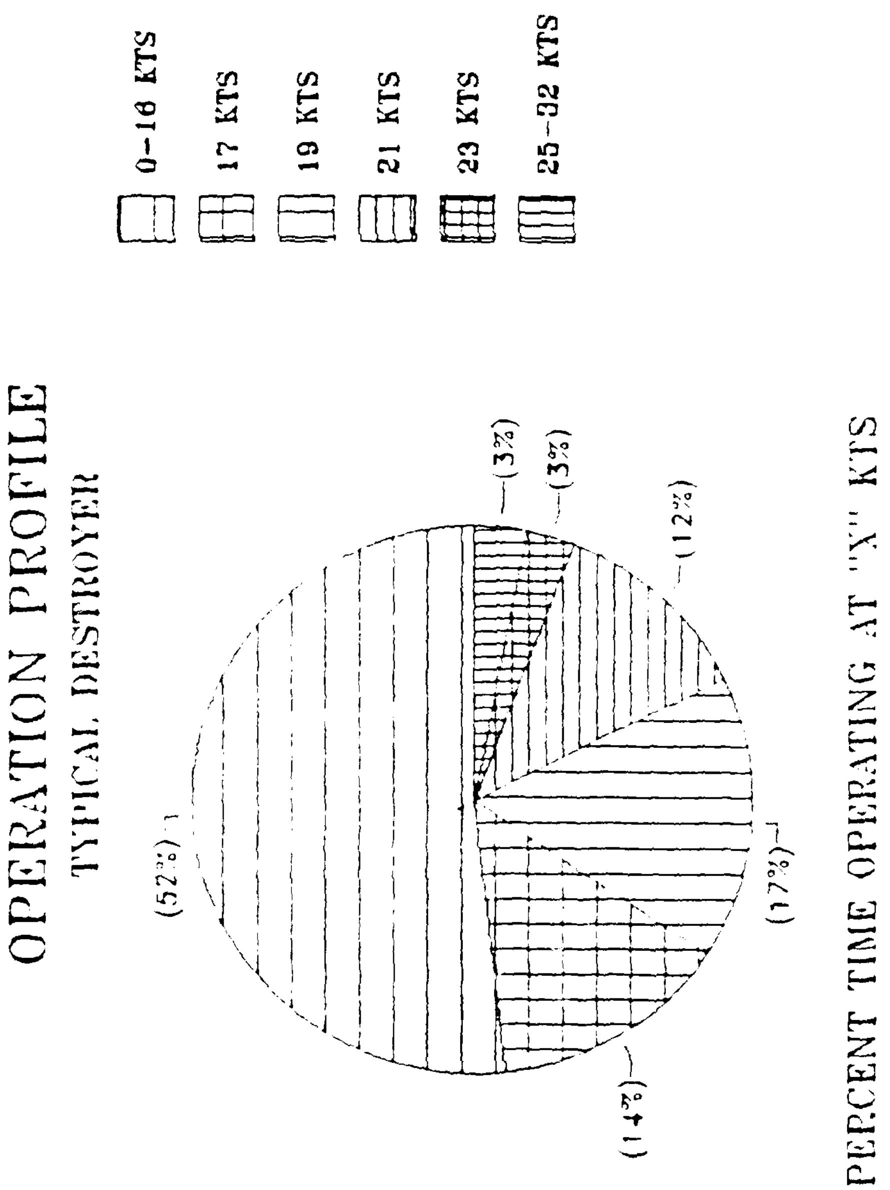

OPERATION PROFILE
TYPICAL DESTROYER
0-16 KTS
17 KTS
19 KTS
21 KTS
23 KTS
25-32 KTS
(52%)
(3%)
(3%)
(12%)
(17%)
(14%)
PERCENT TIME OPERATING AT "X" KTS

FIGURE (20)

is the specific fuel consumption for the power plant in units of lbs of fuel/hp-hr. For this analysis the same propulsion plant and PC values as a function of speed were assumed for each hull form. Total EHP incorporated adjustments for appendage resistance and air resistance. Values for total EHP, specific fuel consumption, and propulsive coefficient for the Spruance at various speeds are available in the same Naval Engineers Journal article that detailed the operation profile of the Spruance (Schlappi, 1982). These values are listed in tabular form in Appendix B.

Because all powering predictions for this investigation were for speeds between 17 and 35 knots at two knot intervals, adjustments were made to the data available from the Naval Engineers Journal. The values for total EHP, propulsive coefficient, and specific fuel consumption actually used in this analysis are also listed in Appendix B.

Two major assumptions were made in developing the routine used for this fuel consumption analysis. The first assumption is the premise that multiplying the EHP/EHPo ratio calculated from the SRPM data by the value for total EHP for the Spruance will yield an estimate of total EHP for the new hull form. Total EHP differs from the bare hull EHP predicted by SRPM because total EHP accounts for the resistance from appendages and air resistance. These adjustments for these added resistances are often estimated as percentages of the bare hull EHP. Hull forms with the same type and size of appendages, would require the same percentage allowance for appendage resistance. Likewise, designs that have the same configuration above the waterline would require the same percentage allowance for air resistance. Because these allowances are percentages of EHP bare hull, in calculating EHP ratios they would cancel each other. For example:

$$
\begin{aligned}
&(EHP)total/(EHPo)total \\
&\quad = (X\% + Y\% + 1.00)EHP/(X\% + Y\% + 1.00)EHPo \\
&\quad = EHP/EHPo \qquad (8)
\end{aligned}
$$

where X% represents the allowance for appendage resistance, and Y% represents the allowance for air reistance.

The second assumption is that at speeds below 17 knots EHP/EHPo can be estimated as the ratio of wetted surface areas or S/So. The following equation helps to illustrate the basis for this assumption:

$$EHP = (CF + CW + CFD + CA)\ 0.5\ \rho\ V^3 S \qquad (9)$$

where CF is the coefficient for frictional resistance, CW is the coefficient for wave-making resistance, CFD is a form drag factor, and CA is an allowance for surface roughness. The SRPM flow code calculates CF as a function of Reynolds number which depends on a ships length at the waterline. CFD is calculated in the flow code as a function of maximum length, beam, and draft of a ship. Because all the hull forms for this investigation were based on the Spruance as a parent form, the values of CF and CFD can be assumed to be the same at a given speed for each hull design. CA is a constant with a value of 0.0005 for the SRPM flow code. For the same speed and in the same water conditions, both and V are the same for different hull forms. This leaves the coefficient for wave-making resistance as a variable. As speed decreases, the contribution of wave-making resistance to total resistance decreases. At low speeds, CW can be estimated as being equal to CWo. This effectively reduces the calculation of EHP/EHPo to S/So:

$$EHP/EHPo \approx (CT\ S)/(CTo\ So) \approx S/So \qquad (10)$$

Based on these assumptions and the information contained in Appendix B, a spread sheet routine was developed to convert the EHP data from the SRPM flow code to estimates of fuel requirements.

C. RESULTS: Figures (21) through (26) show the results of the fuel consumption analysis in terms of long tons of fuel required for every 1000 hours underway, and in terms of percentage change from the fuel requirements for the Spruance with the SQS-53 sonar dome. The "0'" bars refer to the domeless design. The other lengths refer to the length of array that each dome is designed to house.

D. DISCUSSION OF RESULTS: The reference value for the bar graphs illustrating percentage change in fuel requirements is the amount of fuel required by the Spruance with the SQS-53 sonar dome. For every 1000 hours underway, the Spruance would require 2914 long tons of fuel to meet the operation profile given in Figure (20). The domeless design would require 6.4% less fuel to meet the same operation profile. The amount of fuel required by the designs that could incorporate sonar domes housing 160 foot long arrays is less than the amount of fuel for designs with sonar domes housing 80 foot arrays. This is most evident in Figure (25). The decrease results from the shifts of the maximums and minimums in the EHP/EHPo curves for these designs. The greatest increase in fuel requirements predicted by this investigation would be associated with the B3 dome designed to carry 80 foot arrays. A Spruance hull with this type of

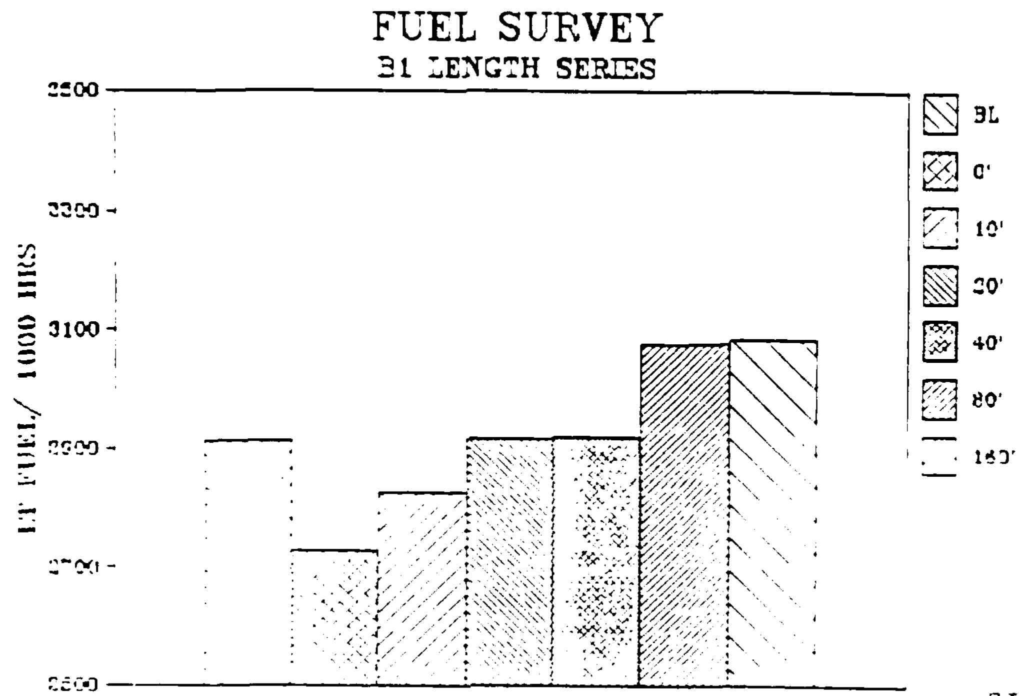


FIGURE (21)

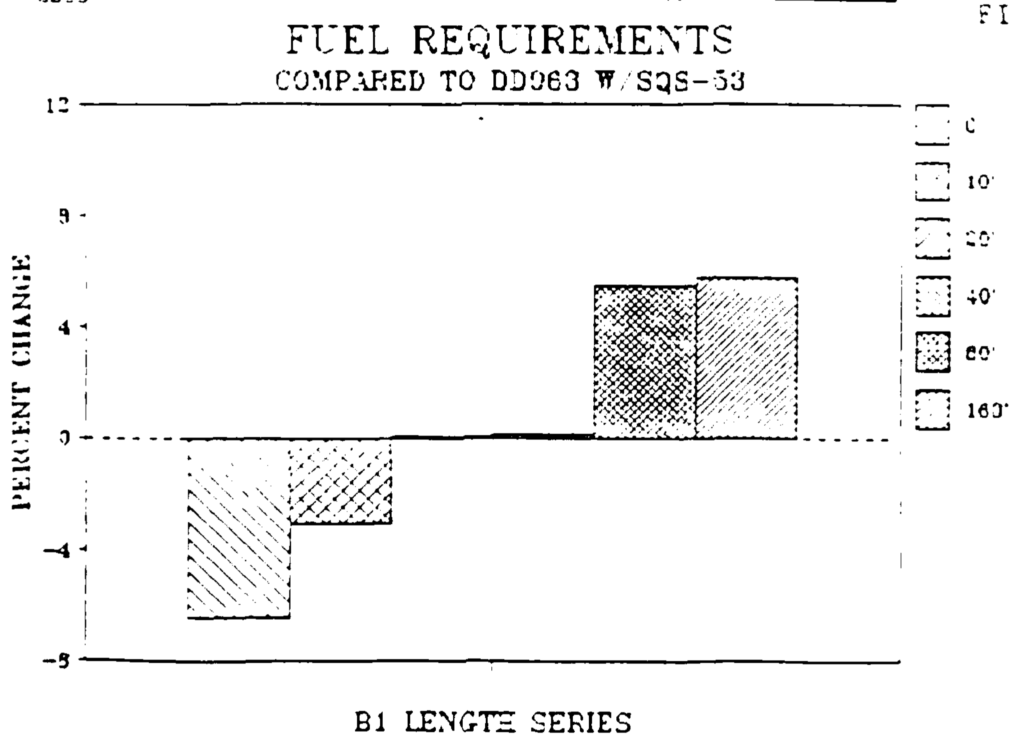
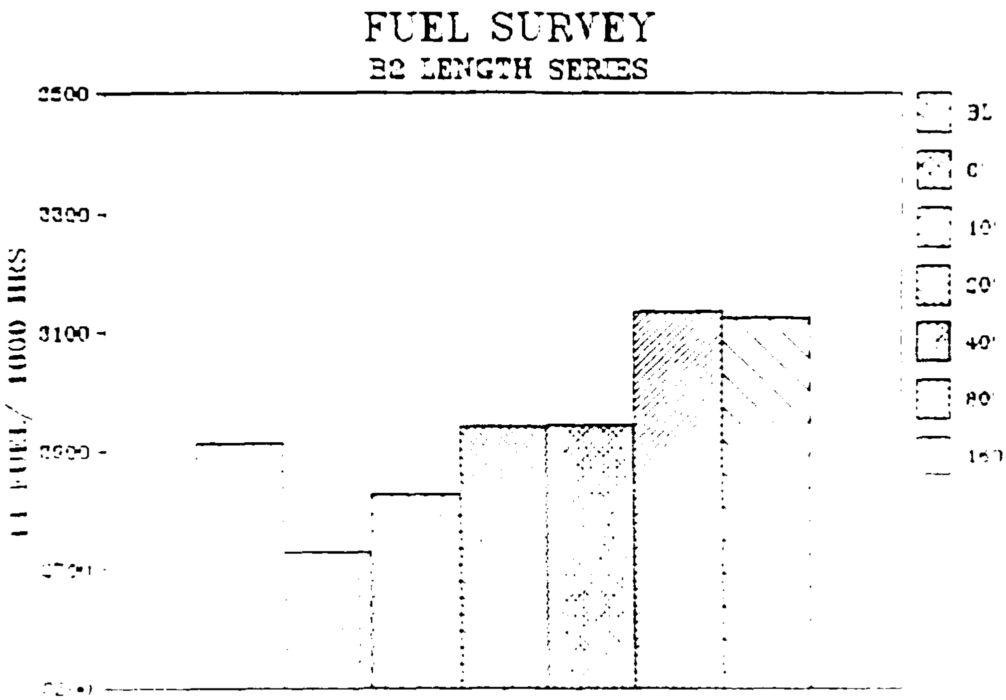
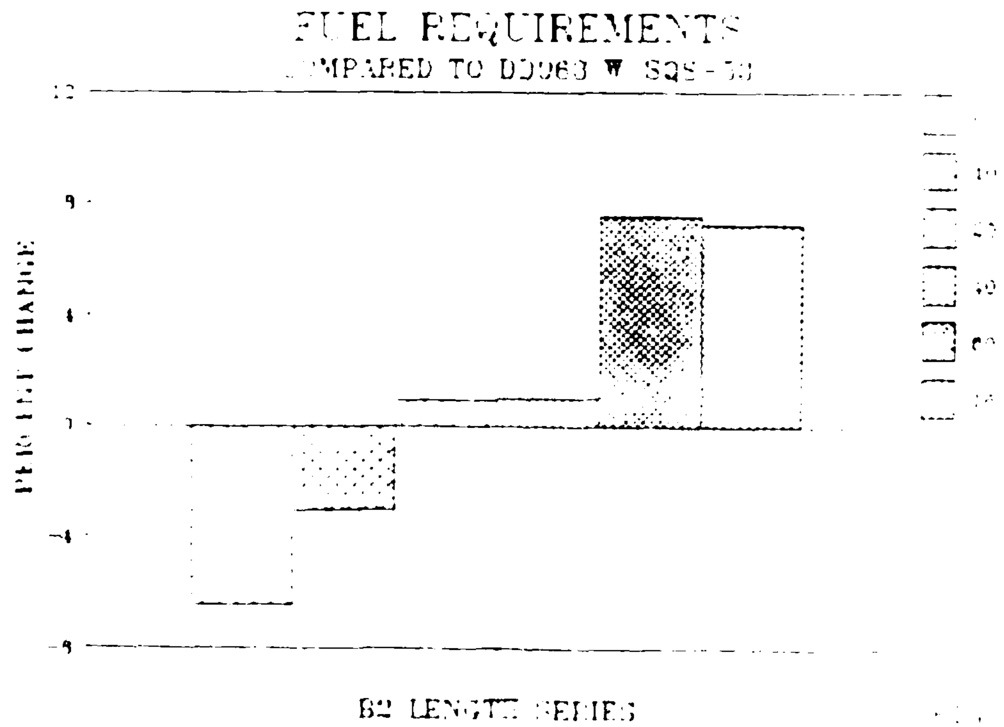


FIGURE (22)


FUEL SURVEY
B2 LENGTH SERIES
3100
FUEL/ 1000 HRS


PERCENT CHANGE
B2 LENGTH SERIES

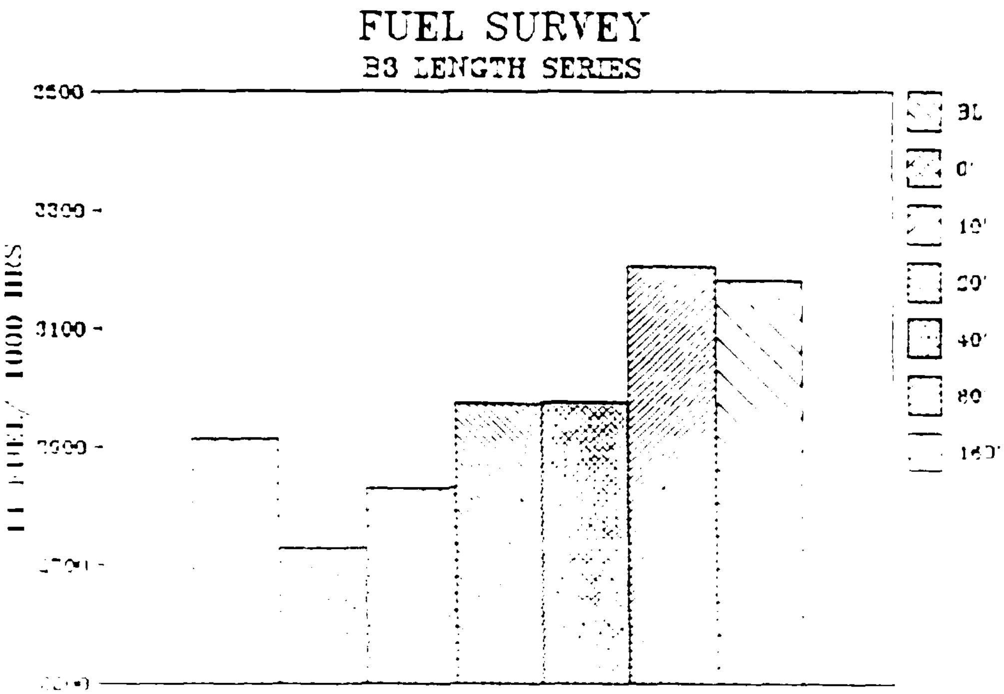


FIGURE (25)

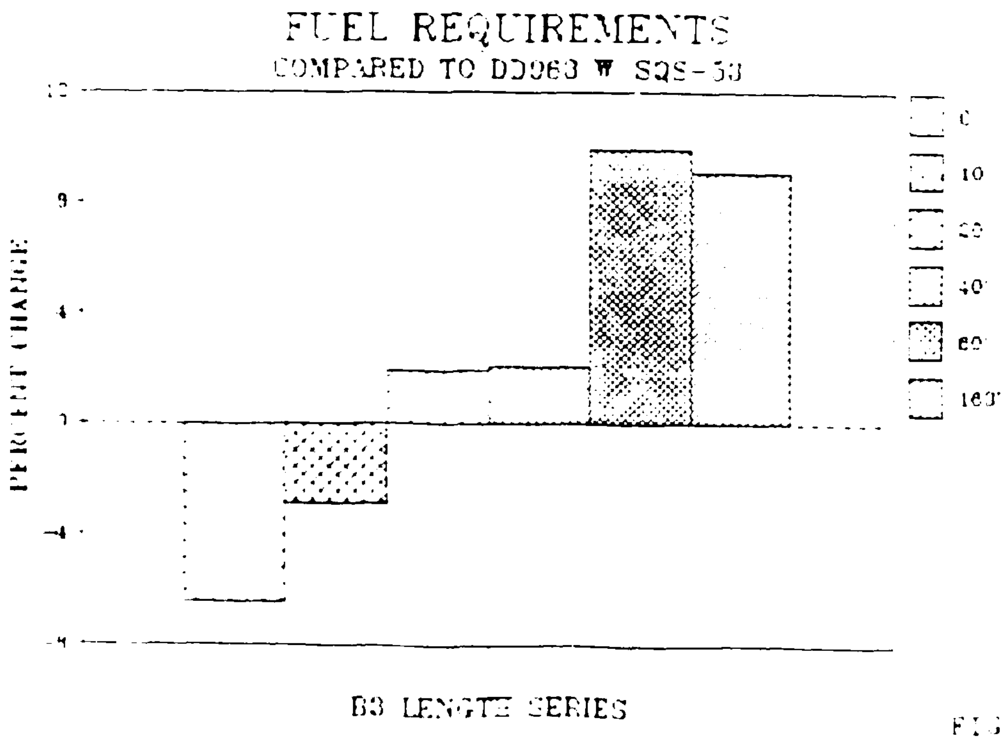


FIGURE 26

dome would require less than 10% more fuel than the same hull with the SQS-53 dome. This represents the worse case evaluated in this study.

V. TRADE-OFF ANALYSIS

A. SONAR CAPABILITIES: The underlying concept for this entire investigation was that an increase in the length of a passive sonar array would yield a significant improvement in the performance capabilities of a sonar system. The actual characteristic that would be improved by increasing array length and thus array surface area is directivity index (DI). This term, which is expressed in decibels, is a measure of a system's ability to discriminate between the signal to be detected unwanted noise (Frieden, 1985). Directivity index follows a logarithmic function which depends on the frequency of the signal to be detected and the total surface area of the array:

$$DI = 10 \log [(4 \text{ PI } A)/(\lambda^2)] \tag{11}$$

$$\lambda = c/f \tag{12}$$

where DI is directivity index expressed in decibels, A is surface area of the array, λ is wave length of the signal, c is the speed of sound in water, and f is the frequency of the signal.

Figure (27) shows the changes in directivity index at two different signal frequencies that would result from increasing the length of arrays with a constant 8 foot depth. For each gain of +3 dB signal strength received at the array would double. The directivity index for a system employing 160 foot arrays would be +12 dB that of a system with 10 foot arrays; this represents a signal strength for the longer array sixteen times that of the 10 foot array.

B. FUEL COSTS: The results from the fuel consumption analysis were converted to monetary figures on the basis that there are 6.77 barrels of fuel in every long ton of fuel and that the price of fuel is $22/barrel. Because the type of arrays used for the SQS-53 sonar are not long planar arrays, no direct comparison of directivity indices could be made for the unconventional dome housed sonars referenced to the DD 963. Instead, the reference for the trade-off anlysis is the Spruance hull with a sonar dome designed to house 10 foot arrays performing the same operations as the DD 963. For the B3 dome design, such a destroyer would require 2727 long tons of fuel for every 1000 hours underway; this would cost $406 for every hour of operation.

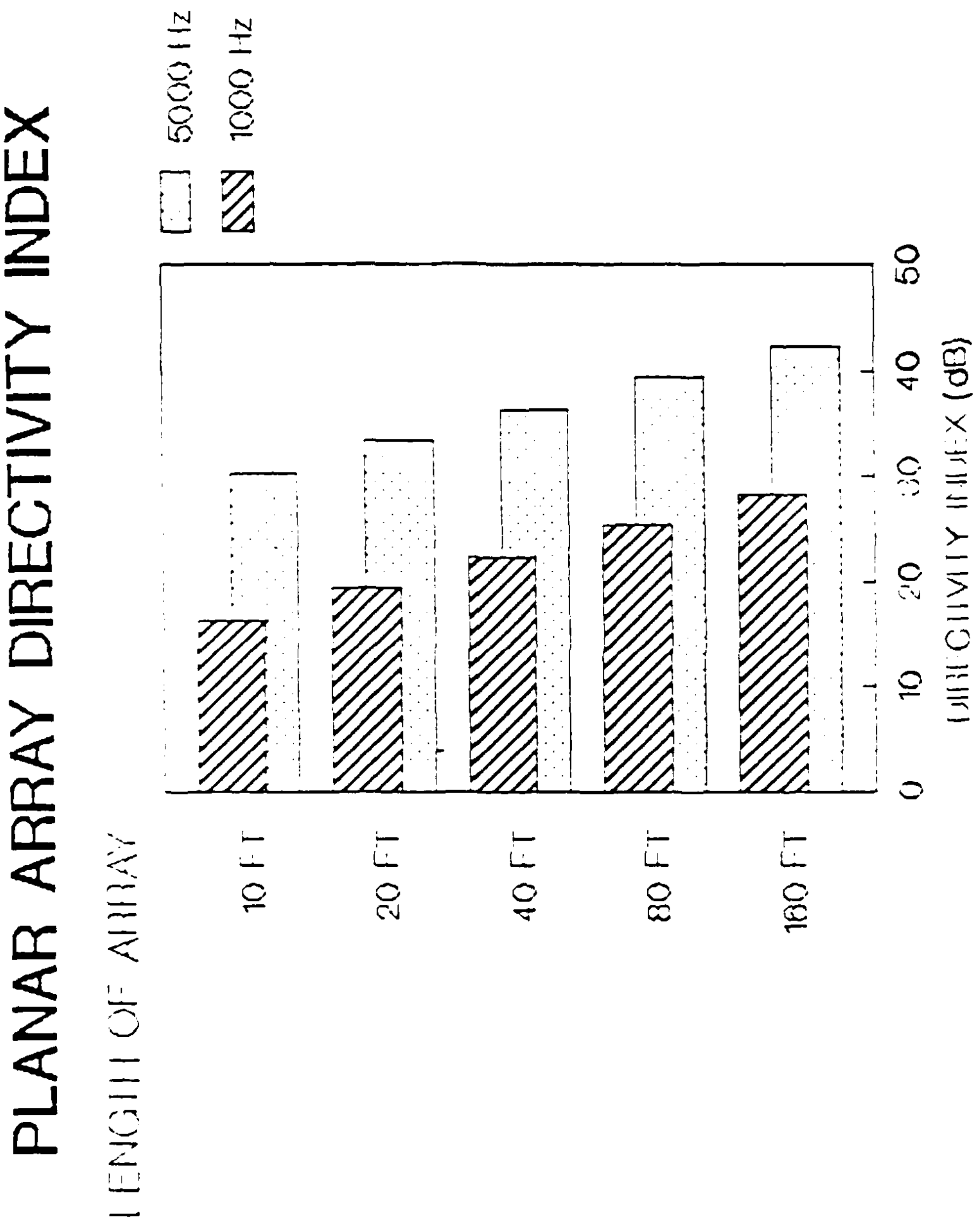

PLANAR ARRAY DIRECTIVITY INDEX
LENGTH OF ARRAY
5000 Hz
1000 Hz
10 FT
20 FT
40 FT
80 FT
160 FT
0
10
20
30
40
50
DIRECTIVITY INDEX (dB)

FIGURE (27)

C. RESULTS: Figures (28) through (30) show the trade-offs in terms of fueling costs necessary to gain different levels of improvement in passive sonar capabilities for the B1, B2, and B3 series of sonar domes.

D. DISCUSSION OF RESULTS: The maximum penalty in terms of fuel costs that was evaluated in this analysis is the additional $55 an hour that would have to be alloted for a Spruance destroyer designed with a B3 shape dome housing 80 foot arrays performing the same operations as the DD 963. This $55/hour penalty is referenced to the cost per hour of operating a destroyer with the B3 dome designed to house 10 foot arrays. The corresponding improvement in directivity index for the sonar with 80 foot arrays would be an increase of signal strength eight times that for the sonar with 10 foot arrays. Table (1) summarizes the gain in directivity index and the corresponding change in fueling costs per hour for the various sonar dome designs evaluated in the length series study.

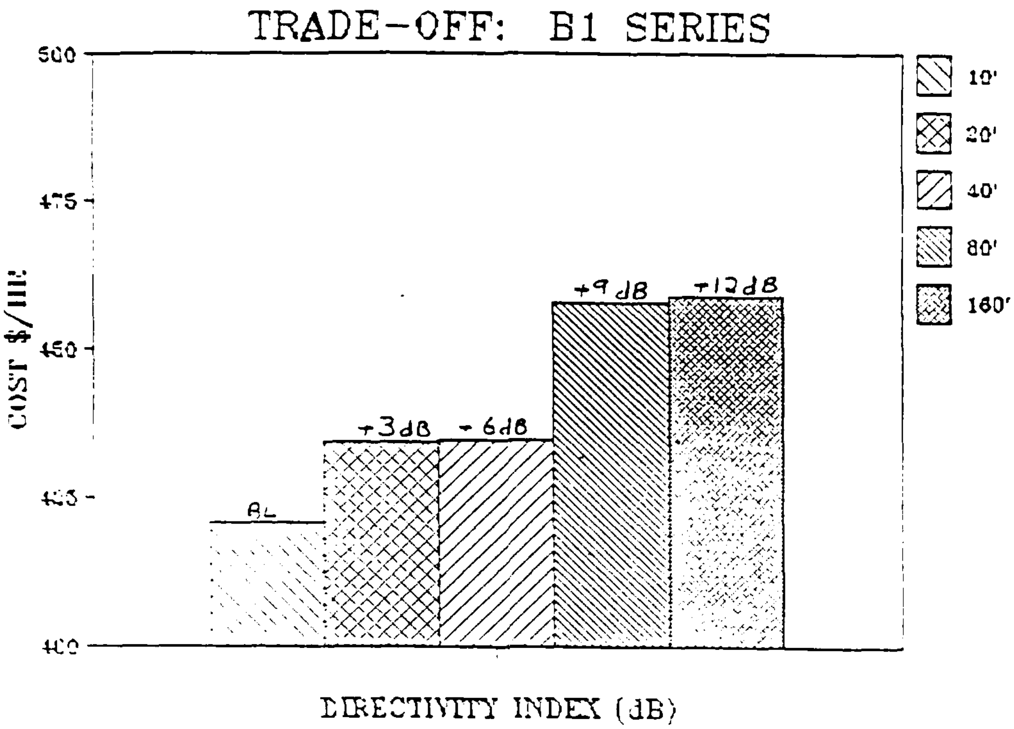

TRADE-OFF: B1 SERIES
500
475
450
400
COST $/HE
BL
+3dB
+6dB
+9dB
+12dB
10'
20'
40'
80'
160'
DIRECTIVITY INDEX (dB)

FIGURE (28)

TRADE-OFF: B2 SERIES

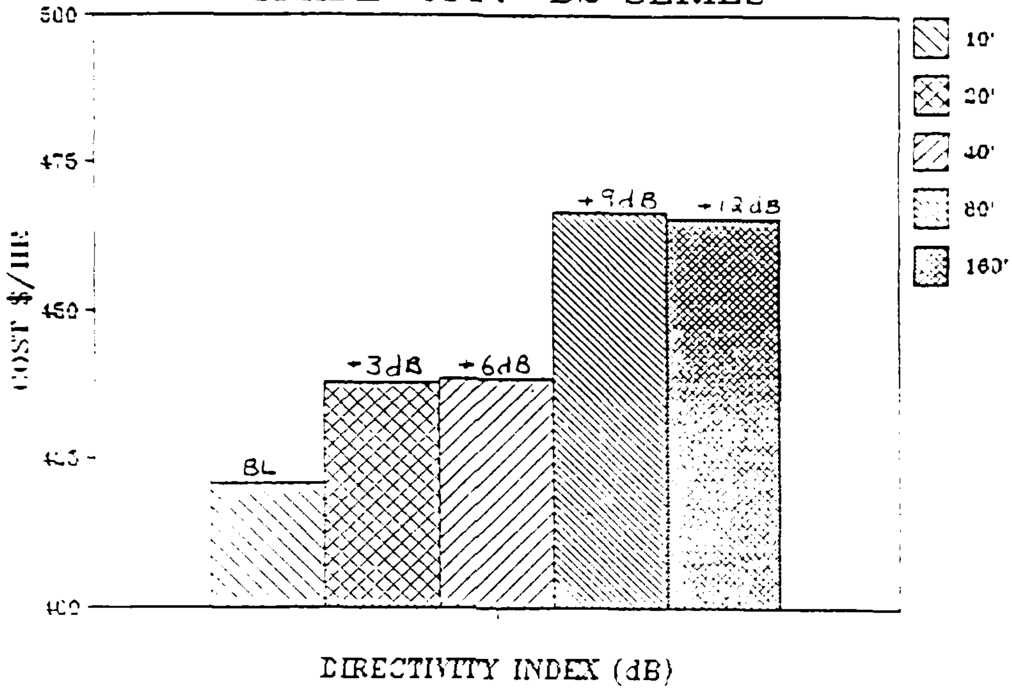


FIGURE 29

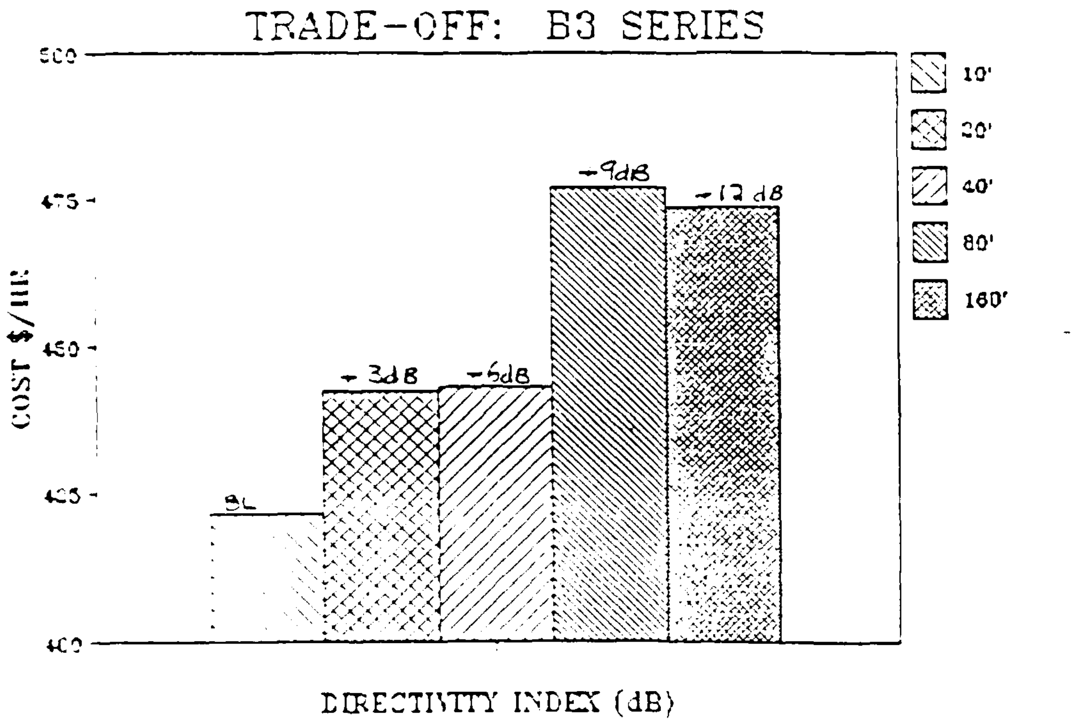


FIGURE (30)

TRADE-OFF SUMMARY

PENALTY IN DOLLARS PER HOUR

DI GAIN (dB)	B1	B2	B3
[illegible]	$13	$17	$21
[illegible]	$14	$18	$21
[illegible]	$37	$46	$55
[illegible]	$38	$45	$52

TABLE (1)

CONCLUSIONS

From the investigation outlined in this report, the following general conclusions can be drawn about the design of unconventional sonar domes:

1. Changing the longitudinal length of a below-baseline, prismatic dome changes the speeds at which relative increases or decreases in predicted effective horsepower occur.
2. Changing the cross-sectional shape and the cross-sectional area of a below-baseline dome affects only the magnitude of the changes in predicted effective horsepower for a given speed.
3. Use of long passive planar sonar arrays can yield significant improvements in the directivity index of a sonar system.
4. The estimated penalty in terms of fuel costs paid for incorporating a large, unconventional sonar dome in the design of a destroyer is not prohibitively large; the value to the destroyer's overall mission of improving sonar capabilites through use of long passive planar arrays warrants investigation.

5. The greatest advantage of the integrated Fastship hull form design and Ship Resistance Prediction Method flow code system set-up at the U.S. Naval Academy Hydromechanics Laboratory is speed.
6. Because this integrated system is resident "in-house" at the Naval Academy, another advantage of the system is cost compared to contracting for time on super-computers to run more sophisticated flow codes.

SUGGESTIONS FOR FUTURE WORK

As a follow-on to the research conducted for this investigation, future studies of unconventional sonar domes should consider:

1. Verification of the SRPM computer analyzed powering predictions from this investigation with model tests.
2. Investigation of the effects of eddy-making resistance for sonar domes on powering predictions and sonar performance.
3. Investigation of the effects on powering estimates of systematically varying the location of the sonar dome along the longitudinal axis.

4. The structural design of long, below-baseline domes.
5. The effects on seakeeping and maneuvering caused by long, below-baseline domes.

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3. Science Applications International Corporation for developing and providing the SRPM flow code.
4. Mr. Dennis Kingsley of the Naval Academy Hydromechanics Laboratory for coordinating the various computer systems and assisting in evaluating data.
5. The other members of the Naval Academy Hydromechanics Laboratory staff for their advice and guidance.
6. And, most importantly, Dr. Bruce Johnson of the USNA Naval Systems Engineering Department who served as the principal advisor for this Trident Project.

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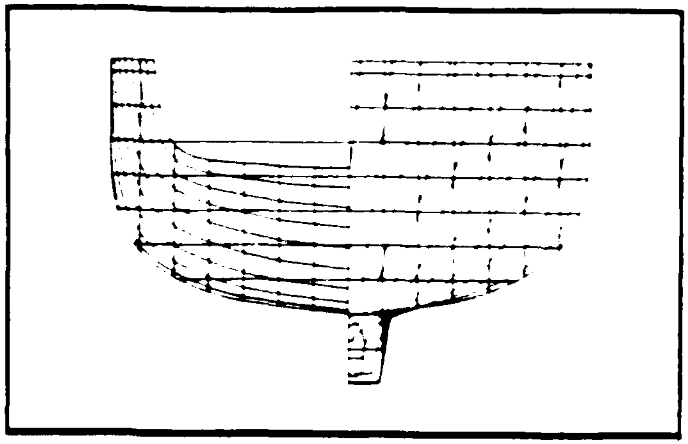
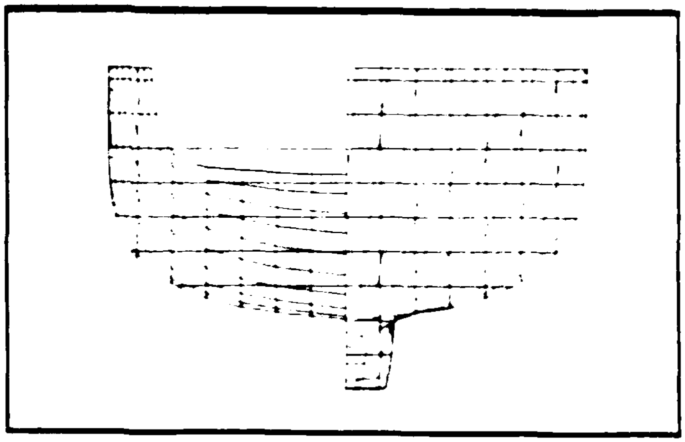
APPENDIX A

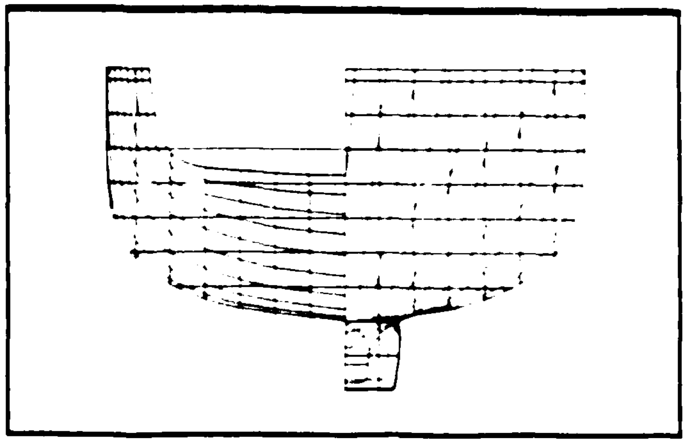
DOME A1



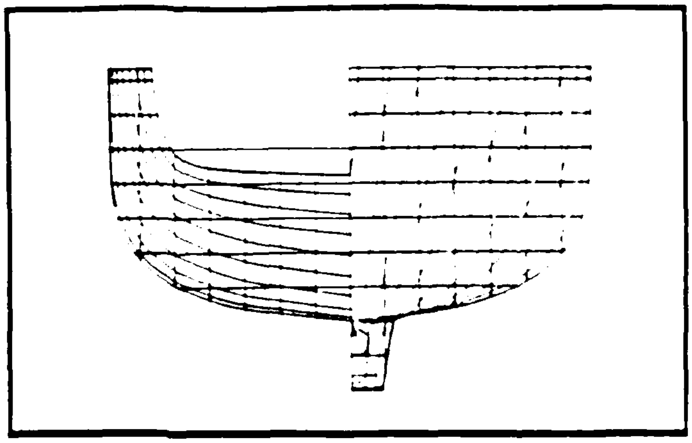
DOME A2



DOME A3



DOME B1



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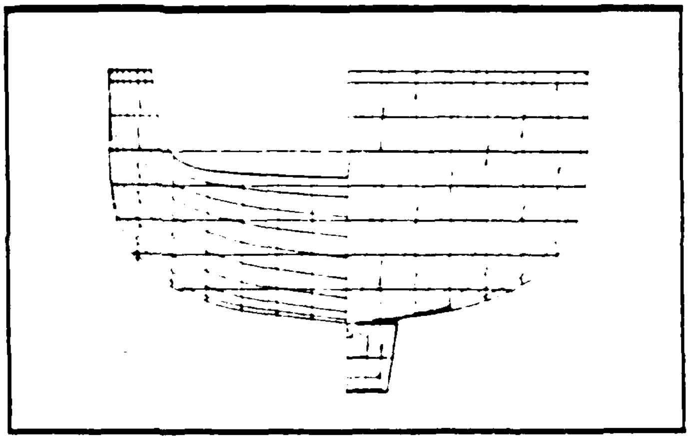

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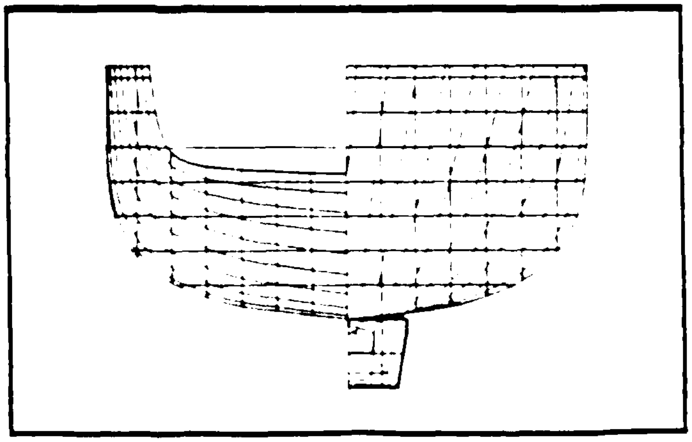
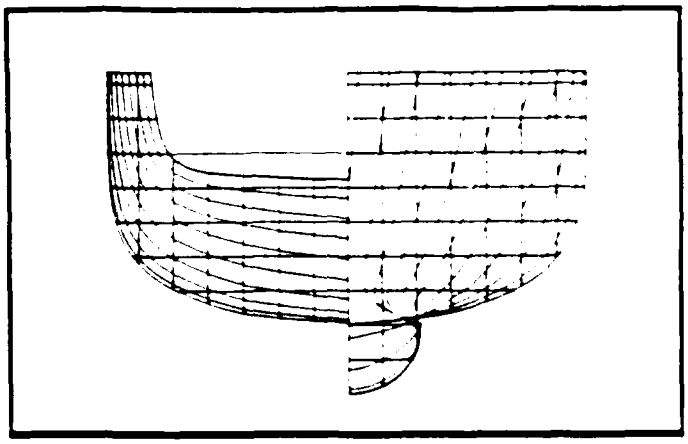


FIGURE (A2)

DOME C1



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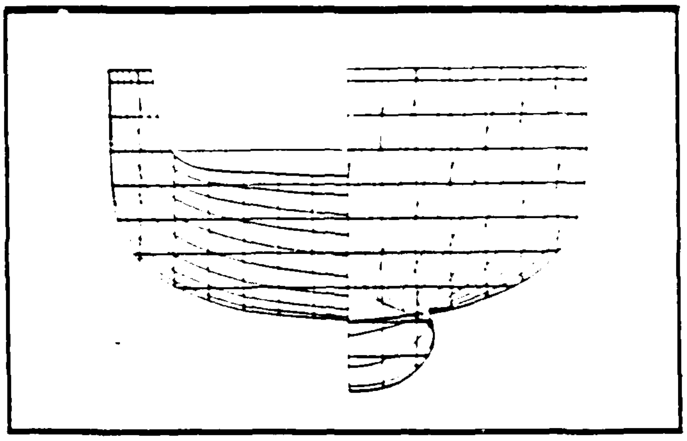

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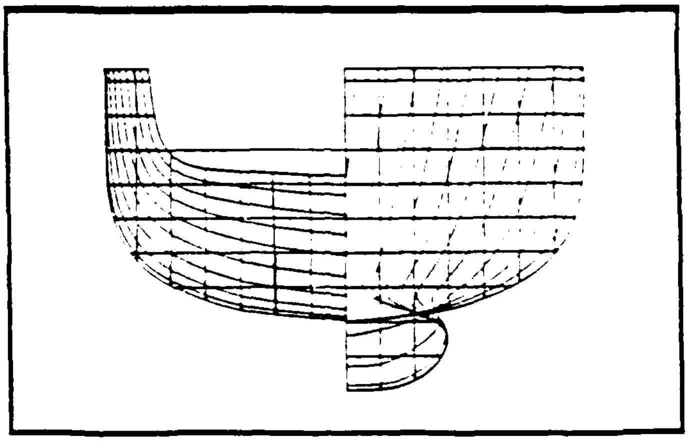
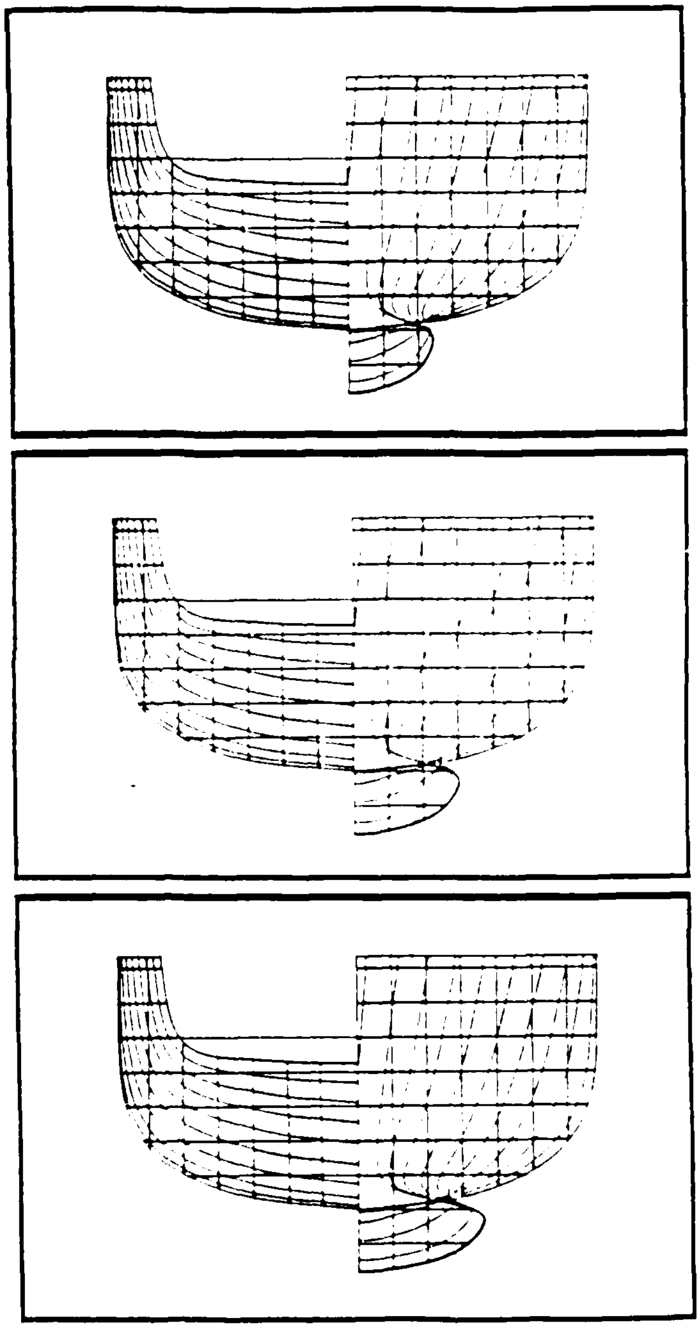


FIGURE (A3)



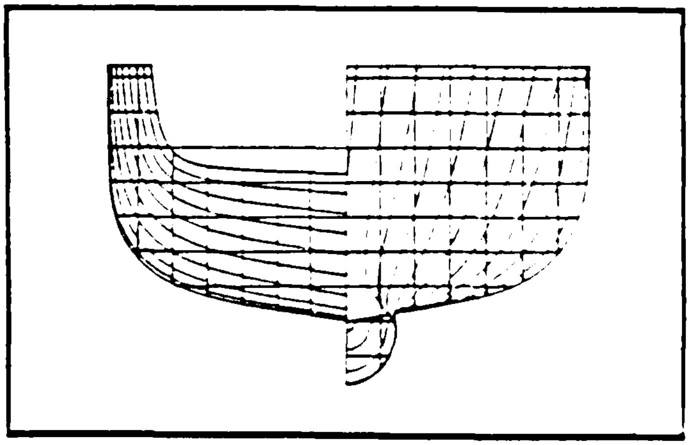
DOME D1

DOME D2

DOME D3

FIGURE (A4)

DOME E1



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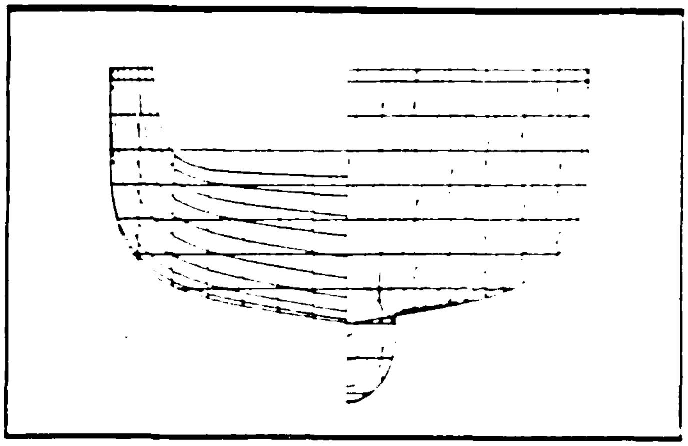

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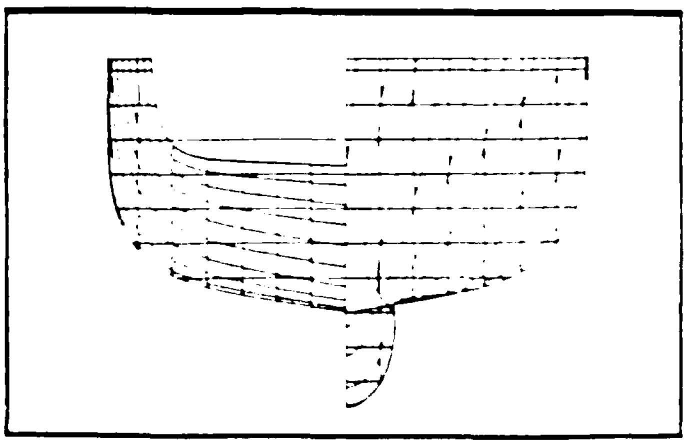

FIGURE [illegible]

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[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]

[illegible]

APPENDIX B

DD963 POWERING DATA (SCHLAPPI, 1982)

SPEED KTS	HR/ YR	TOTAL EHP	EACH PROPELLER EHP	PC	SHP	SFC	TON/YR
0-10	357	700	350	0.66	530	1.00	85
11	189	1,700	850	0.66	1,290	1.00	108
12	201	2,170	1,080	0.66	1,700	1.00	153
13	210	2,790	1,390	0.64	2,400	.90	202
14	213	3,410	1,700	0.63	2,700	.85	218
15	204	4,240	2,100		3,300	.80	240
16	183	5,070	2,500		4,000	.70	229
17	198	6,100	3,100		4,900	.65	282
18	216	7,140	3,600		5,800	.61	341
19	231	8,420	4,200		6,700	.58	401
20	267	9,700	4,800		7,600	.55	498
21	225	11,200	5,600		8,900	.52	465
22	129	12,700	6,300		10,000	.50	288
23	45	14,450	7,200		11,400	.48	110
24	39	16,200	8,100		12,900	.46	103
25	21	18,450	9,200		14,600	.45	61
26	15	20,700	10,000		15,900	.44	47
27	12	24,150	12,000		19,000	.43	44
28	9	27,600	13,800		22,000	.48	42
29	9	33,450	16,700	0.63	26,600	.46	49
30	9	39,300	19,650	0.62	33,400	.43	58
31	9	46,150	23,070	0.62	37,200	.42	60
32	9	53,000	26,500	0.61	43,400	.41	72
TOTAL	3,000						4,156

TOTAL ANNUAL FUEL – 8,312 TON

SPEED KTS	%TIME	ADJUSTED DATA PC	SFC	EHP (TWO PROPS)
0-16	51.9	0.653	0.950	2870
17-18	13.8	0.63	0.630	6700
19-20	16.6	0.63	0.565	9000
21-22	11.8	0.63	0.510	11900
23-24	2.8	0.63	0.470	15300
25-26	0.8	0.63	0.445	19200
27-28	0.8	0.63	0.455	25800
29-30	0.8	0.625	0.445	36350
31-32	0.8	0.615	0.415	49570

END

8-87

DTIC